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Improving the Behavior of Steel Plate Shear Wall Using Double Infill Plates

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Abstract. Steel Plate Shear Wall (SPSW) has indicated suitable performance in numerical studies by researchers as well as in past earthquakes. Although this system has a considerable advantage, it requires huge columns to resist stress due to the infill plate, and this is one of the main dilemmas relating to this system. Also, increasing the infill plate made the system form plastic hinges in the columns instead of the infill plate and beam. To solve this problem, herein, an innovative model of SPSW is proposed as an alternative to the traditional type of steel shear wall, namely the use of Double Infill Plates for SPSW (DIP-SSW). The use of DIP-SSW as a resistance system against lateral loads, also results in space savings. The present numerical finite element investigation was performed by parametric study and consideration of the nonlinear behavior of this system. The results of the parametric study have been addressed. Also, the results showed that the DIP-SSW has an excellent ductility factor and capability of energy absorption under lateral loads.

Keywords: steel shear wall; double infill plates; stiffness; ductility.

1. Introduction

Steel Plate Shear Walls (SPSWs) relying on the infill plate, resist against lateral loadings. The high slenderness of the infill plate made it buckle at the elastic zone. The elastic bucking of the infill plate is not the ultimate load carrying of the system. By post-bucking, the main resistance of the system is occurred after bucking that is known as diagonal filed action [1]. This phenomenon was introduced by Wagner [2]. Then, researchers [3,4] used this theory to design girders and then was used to design of SPSWs based on the findings of researchers at the University of Alberta [5,6].

Experimental and numerical studies till now have demonstrated the capability of the SPSW system as a system with considerable ductility, high lateral stiffness, and lateral strength [7-14]. Thereafter, the SPSW design requirements were reported in FEMA450 [15], AISC 341 [16], and AISC Design Guide 20 [17]. Several researchers have attempted to prevent elastic buckling of the infill plate. They proposed to use of LYP steel [18-22], adding dampers [23], changing the mechanism of SPSW by stiffeners [24-26], covering the infill plate using concrete [27-30], separating the infill wall from the boundary frame [31,32], utilizing semi-supported SPSW [33,34], covering the infill plate by FRP [35], semi-disconnected SPSW [36].

Although the mentioned idea improves the behavior of SPSW, it imposes an additional cost on the structures. Therefore, in this study, an innovative idea of SPSW is presented to reduce the imposed additional cost to the structures.

In this study, Double Infill Plates for Steel plate Shear Walls (DIP-SSW) are proposed to be used. The main feature of this system is that the shear stress of the column is reduced, and the post-buckling of the infill plates has governed the behavior of the system. It is also useful for the architect aspect because less space is occupied. The nonlinear behavior of the DIP-SSW is studied in many aspects.

2. Methodology

2.1. Numerical models

Rezai [37] showed that the strains developed in the top and bottom flanges of the story beams were relatively small.

Fig. 1 illustrates the SPSW model used for the parametric study. The ANSYS computer program was selected to simulate the Finite Element (FE) analysis and modeling. All elements were simulated using the SHELL element.

The model consists of a single panel bounded by two rigid beams at the top and bottom. In this study and to start with, a single-story single-bay SPSW having L = h = 2700 mm, $\beta_1 = L/h = 1$, and t_p=3 mm (Model DB-t3), as illustrated in Fig. 1, was designed according to the AISC 341-05 [16] and the AISC Design Guide 20 [17] rules and provisions, where L and h are the width and the height of the infill plate, respectively, and t_p is the thickness of infill plate. After that, the L had increased 1.5 times, and the t_p had increased 1.5 and 2 times, while the column cross-section and the panel/column height kept constant. The different models are listed in Table 1.

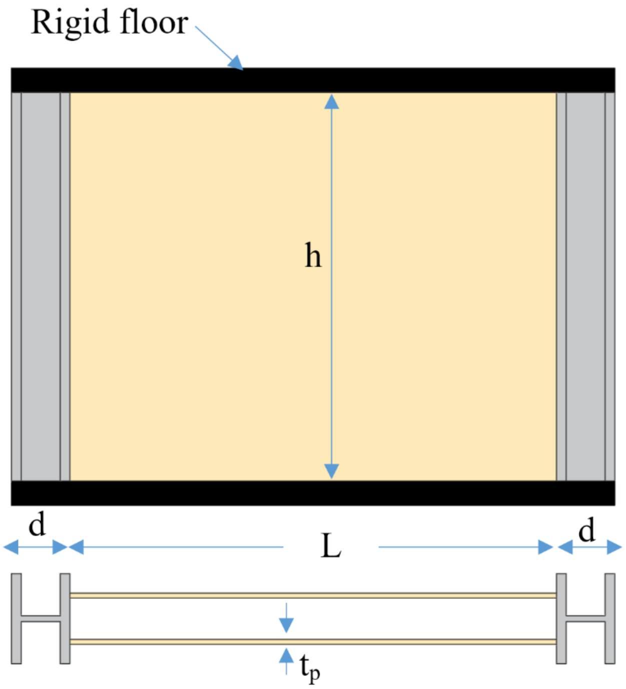


Fig. 1: A selected model for the parametric study.

Table 1: Numerical models.

Model	t_p (mm)	h (mm)	L (mm)
DB-t3	3	2700	2700
DB-t4.5	4.5	2700	2700
DB-t6	6	2700	2700
DB-t3-L1.5	3	2700	4050
DB-t4.5-L1.5	4.5	2700	4050
DB-t6-L1.5	6	2700	4050

2.2. Material properties and boundary conditions

The ST37 steel was selected for the infill plate and columns materials with a yield stress of 240 MPa, modulus of Elasticity of 200 GPa, and Poisson's ratio of 0.3, respectively.

For the pushover analysis of the FE models, the displacement control method was used. It was considered equal to a drift angle of 2.5% according to the ASCE 7-05 [38].

2.3. Model parameters

In general, the parameters affecting the behavior and capacity of a system are classified into three categories: geometric variables, deformational variables, and loading parameters. The parameters that govern the behavior and capacity of the selected model of steel plate shear wall with rigid floor beams are defined below. Referring to Fig. 1, the geometric variables were defined.

$\beta_1 = L/h$ (Aspect ratio)

$\beta_2 = \frac{t_w L}{2A_c}$ (Ratio of axial stiffness of infill plate to that column)

$\beta_3 = \delta/h$ (Drift index)

$\beta_4 = V/V_{yield}$ (Ratio of shear load to shear yield capacity or normalized base shear)

Using the Von Misses yield criterion, the V_y can be obtained as follows:

$$V_{yield} = 2d.t_p\left(0.577F_y\right) + L.F_y \qquad (1)$$

In these relations, A_c is the cross-sectional area of the columns, δ is the drift of the wall, V is the lateral shear force, V_{yield} is the shear force corresponding to the yielding of whole cross section of the shear wall, and F_y is the yield strength of materials.

Of the above parameters, the normalized base shear β_4, is the loading parameter, while the drift index β_3, is obtained as an output. The remaining β–parameters define the Finite Element (FE) model (Table 2). In terms of limit states design, the ultimate limit state is defined as the maximum value of β_4, and the serviceability limit state can be described in terms of β_3 which is the drift index.

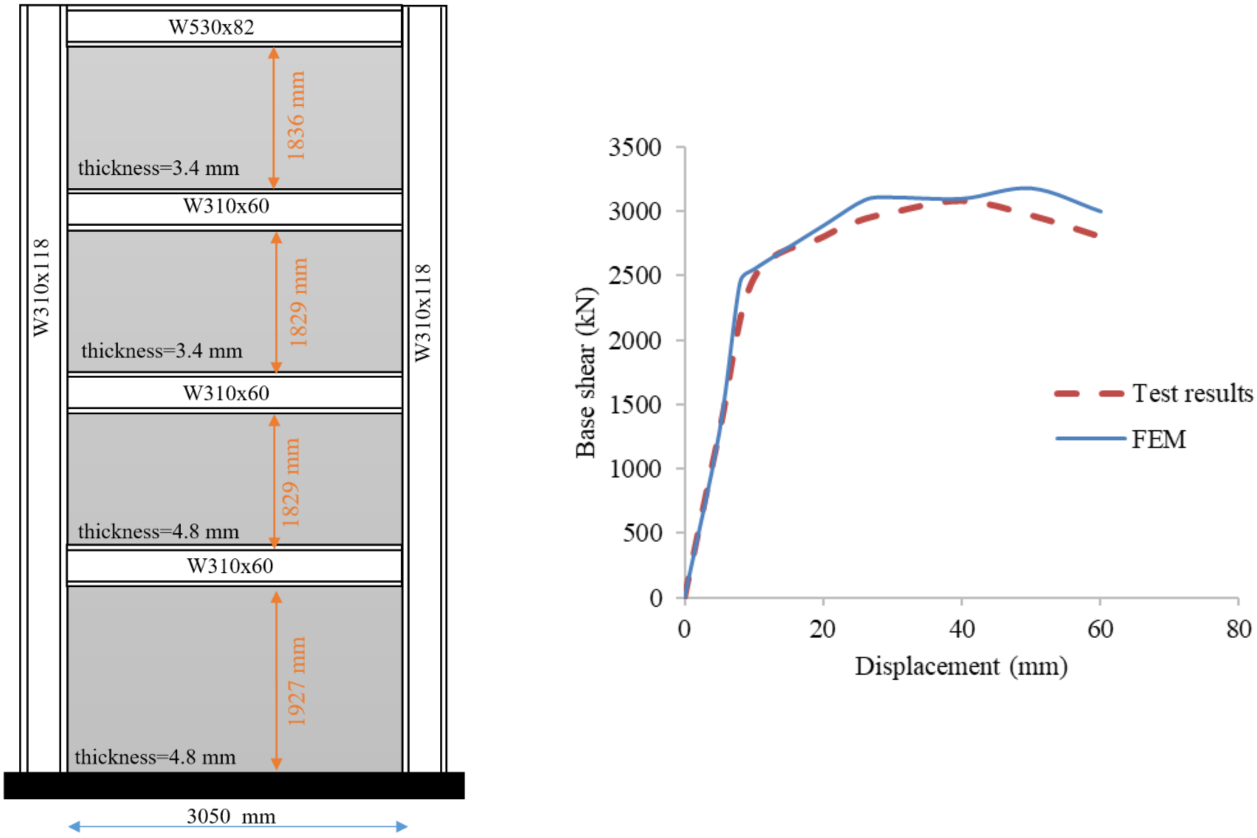
Table 2: Model parameters.

Model	V_y (kN)	β_1	β_2
DB-t3	278	1	0.20
DB-t4.5	334	1	0.30
DB-t6	391	1	0.41
DB-t3-L1.5	334	1.5	0.30
DB-t4.5-L1.5	419	1.5	0.46
DB-t6-L1.5	503	1.5	0.61

Behbahanifard et al. [39] selected eight scale-independent and non-dimensional parameters that have the potential to influence the predicted non-dimensional inelastic pushover curve of steel plate shear walls. It was found that only three of the parameters (aspect ratio, column flexibility, and normalized gravity load) had a significant influence on the behavior and also were relevant to the parametric study of the modified strip model. During the design process, it was found that the normalized gravity load parameter did not vary much (between 0.01 and 0.03). Thus, to maintain a reasonably straightforward design process, the normalized gravity load parameter was not considered in the study. The aspect ratio was varied by changing the length *L* (distance between steel plate shear wall column centerlines), and keeping the story height *h* constant. The column flexibility parameter (defined by the CAN/CSA S16-01 [40]) was varied by using different column cross-sections while keeping the infill plate thickness and aspect ratio constant.

2.4. Verification of the FE results

In order to validate the FE results, the FE results were compared with the experimental results reported in Ref. [35]. The boundary condition, material properties, and other aspects of the SPSW were simulated as the same as the experimental model of Ref. [35]. Fig. 2 shows a good agreement between the FE results and the experimental results.



(a) (b)

Fig. 2. Steel plate shear wall system without crack: (a) test setup, (b) load–displacement response.

3. Discussion and results

3.1. Effect of aspect ratio-β_1

The aspect ratio (β_1) is an important parameter since it is expected that it will strongly influence the inclination of the tension field and the resulting general behavior of the steel plate shear wall. In a narrow and tall shear wall (small aspect ratio), the tension field is close to vertical, which makes the tension field contribution to shear resistance small, and bending becomes the governing factor. In a wide and short shear wall (large aspect ratio), the tension field is more inclined, which results in shear deformations governing the behavior of the shear wall. Changing the aspect ratio in a steel plate shear wall changes the relative stiffness of the columns to the infill plate, and this affects the stiffness and the capacity of the shear wall.

The effect of the infill plate aspect ratio on the behavior of the steel plate shear wall was investigated using four models with aspect ratios of 1.0, 1.5, as shown in Fig. 3. The remaining non-dimensional parameters were kept constant for these models. The other β–parameters were obtained in such a way that the combination of non-dimensional parameters results in practical and reasonable dimensions for each model.

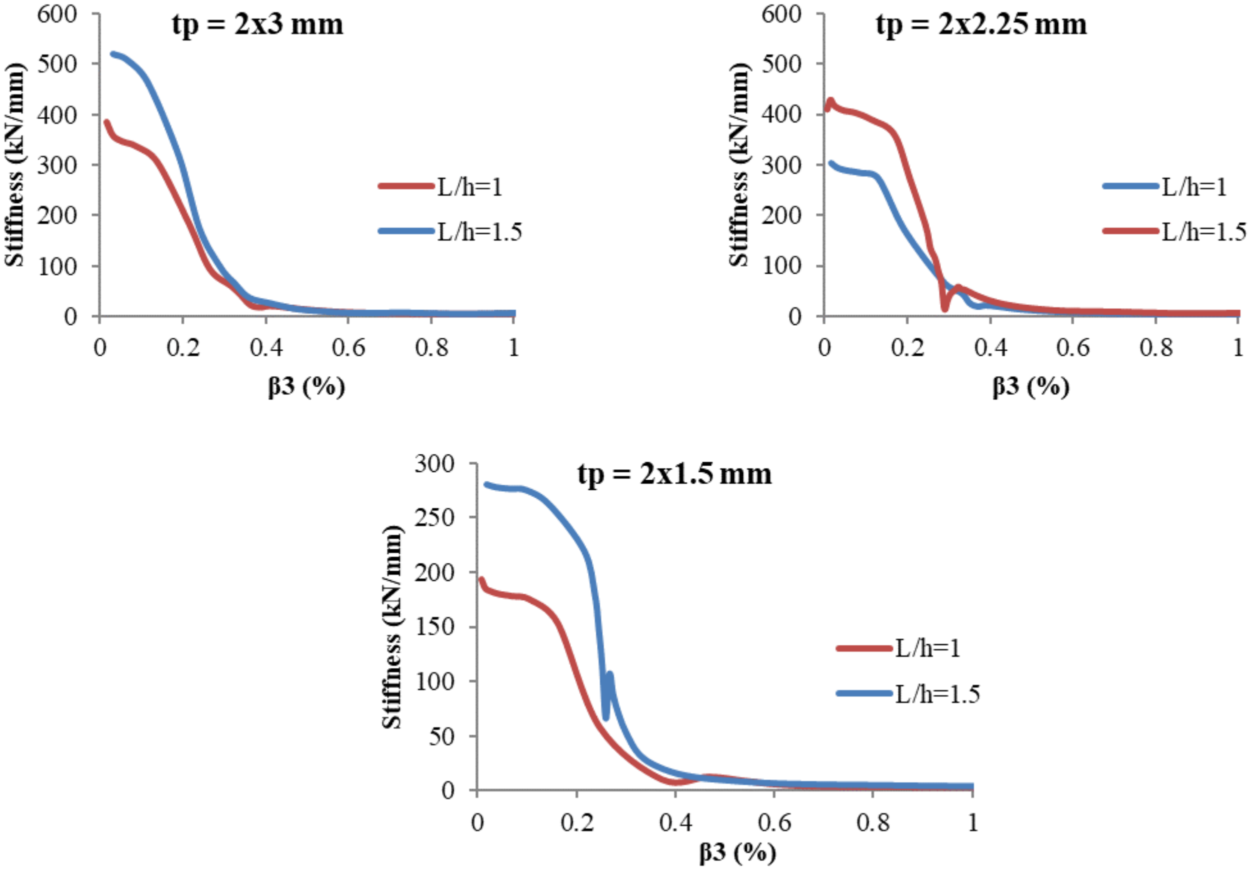


Fig. 3: Stiffness versus $\boldsymbol{\beta_3}$ graph.

3.2. Effect of ratio of axial stiffness of infill plate to that of columns-β_2

The ratio of the in-plane stiffness of the infill plate in the vertical direction to the axial stiffness of the columns (β_2), affects the compressive stress field in the infill plate.

The different values of the β_2 were selected for this investigation, while the other non-dimensional parameters were kept unchanged in the models, as shown in Table 3.

Table 3: β2 values of numerical models.

	β_1=1			β_1=1.5		
Model	DB-t3	DB-t4.5	DB-t6	DB-t3-L1.5	DB-t4.5-L1.5	DB-t6-L1.5
β_2	0.20	0.30	0.41	0.30	0.45	0.61
V_y (kN)	2783.45	3344.29	3905.01	3344.29	4185.56	5026.82
$\frac{V_{y\,(i)}}{V_{y\,(\mathrm{DB-t3-i})}}$	1	1.2	1.4	1	1.25	1.5

Three different values of β_2, namely 0.20, 0.30 (two models), 0.41, 0.45, and 0.61, were selected for this investigation, while the other non-dimensional parameters were kept unchanged in the models. The normalized response is shown in Fig. 4 for different values of β_2. The base shear has reached 80 percent of V_y in all models, but only the β_2=0.20 (DB-t3) reached around 60 percent of V_y. For $\beta_1=1$, by increasing the β_2 from 0.20 to 0.41, the V_y is increased up 1.4 times, whereas for $\beta_1=1.5$, by increasing the β_2 from 0.20 to 0.41, the V_y is increased up to 1.5 times.

Referring to Fig. 4, the axial stiffness ratio, β_2, does not have a considerable effect on the lateral strength and stiffness of the shear wall.

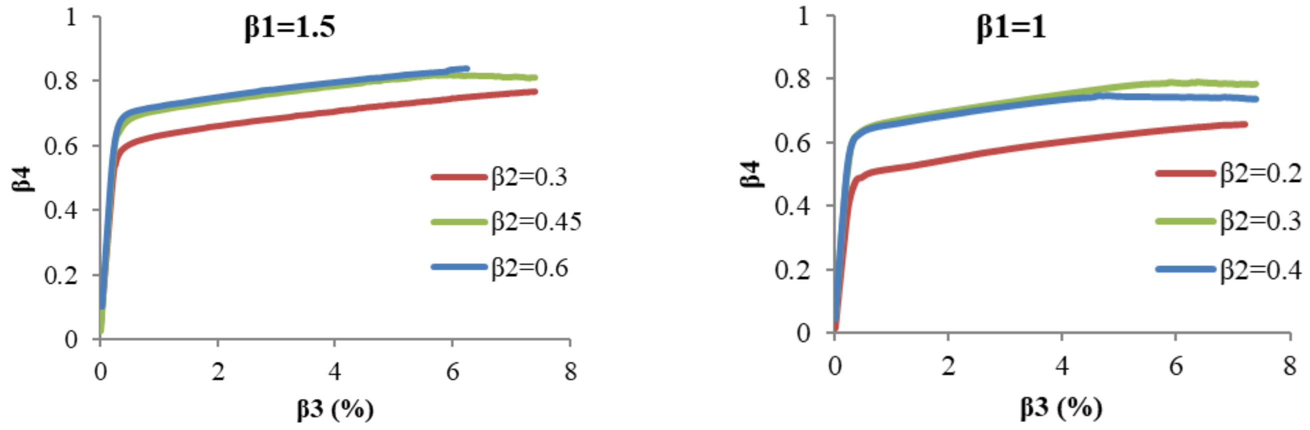
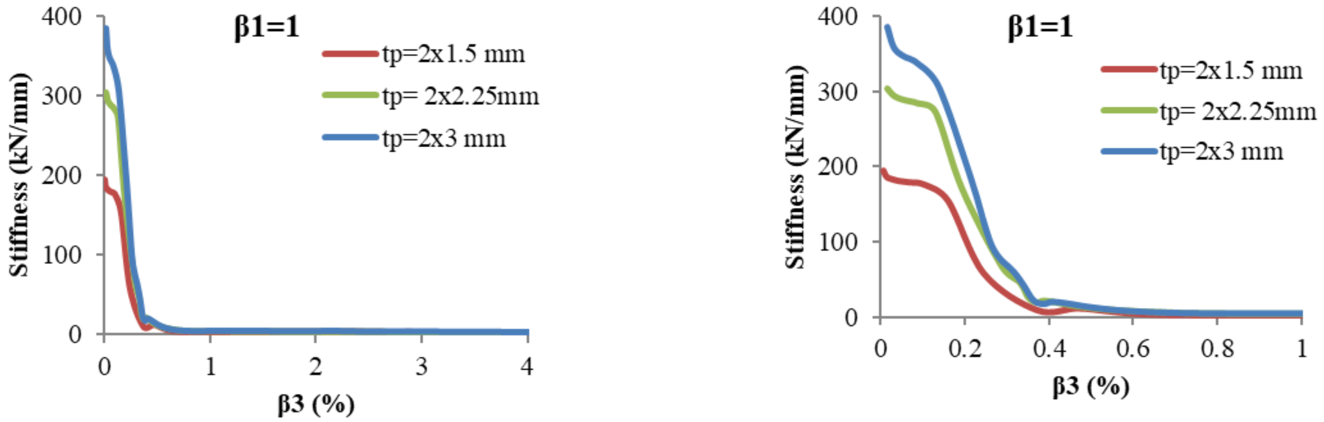


Fig. 4: β_4 versus β_3 graph.

The stiffness curves of DIP-SSWs with β1=1, 1.5 and various infill thicknesses are given in Fig. 5. As shown in Fig. 5, after the drift angle of 0.7%, the infill plate thickness does not have a considerable effect on the stiffness. It should be noted that by increasing the infill plate, the initial lateral stiffness is increased. Nevertheless, after the appearance of diagonal yield zones, which incidentally occur at similar drift angles, the curves tend to converge towards each other.



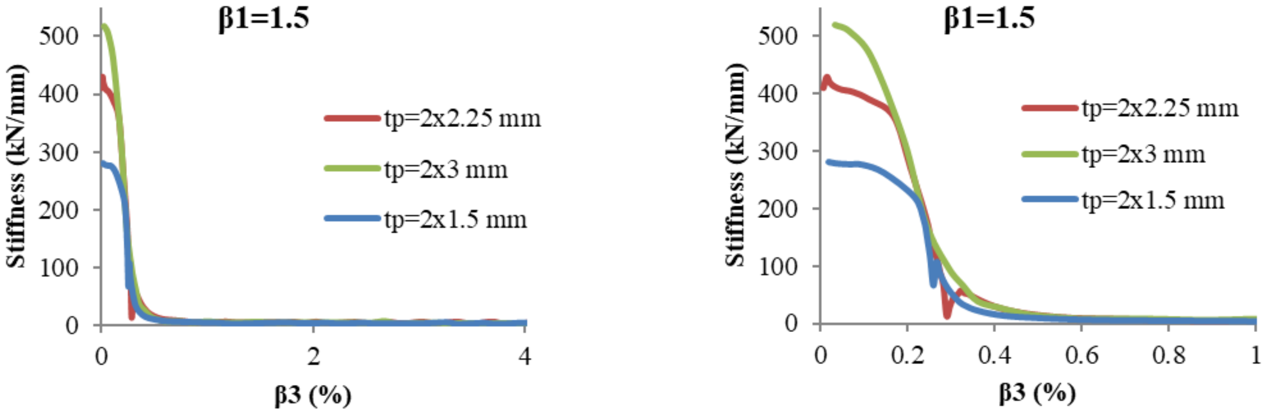


Fig. 5: Stiffness versus β3.

3.3. Structural parameters

3.3.1 Energy absorption

In Fig. 6, the energy dissipation, E_s, of the system is shown. The results indicate that that higher β_1 values increase energy absorption of the DIP-SSW system. Also, by increasing the t_p of the infill plates, the energy absorption capacity of the systems is improved.

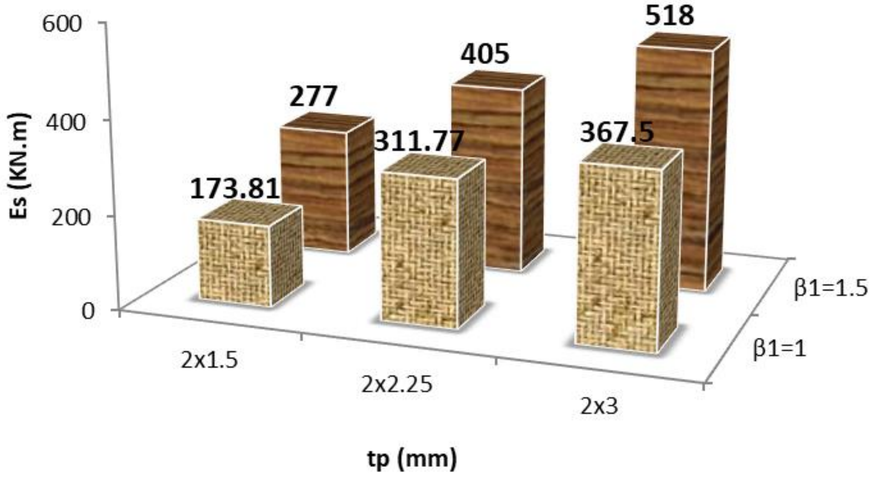


Fig. 6: Energy absorption graph.

3.3.2 Overstrength and Ductility

The overstrength, Ω, and the ductility, μ, of the FE models are listed in Table 4. Referring to the results of Table 4, both β_1 and β_2 are effective on the mentioned parameters. But, they are more effective on the overstrength than ductility. Also, β_1 is more effective than the β_2 for both parameters.

Table 4: Structural parameters.

		μ	Ω
β_1	DB-t3	7.11	1.46
	DB-t4.5	8.44	1.60
	DB-t6	8.44	1.61
β_2	DB-t3-L1.5	7.50	1.32
	DB-t4.5-L1.5	8.44	1.43
	DB-t6-L1.5	8.44	1.54

3.3.3 Elastic stiffness and displacement corresponding to the yielding

In Table 5, the elastic stiffness, K, and displacement that correspond to the yielding, Δ_y, are listed to consider the effect of the β_1 and β_2 on the mentioned parameters. As reported in Table 5, by increasing the thickness of the infill plate, the elastic stiffness K is enhanced, but Δ_y is reduced. Also, increasing the β1 does not have an effect on the Δ_y, whereas by increasing the β_2, both K and Δ_y are improved.

Table 5: Elastic stiffness and displacement corresponding to the yielding

	β_1=1			β_1=1.5		
Model	DB-t3	DB-t4.5	DB-t6	DB-t3-L1.5	DB-t4.5-L1.5	DB-t6-L1.5
β_2	0.20	0.30	0.41	0.30	0.45	0.61
Δ_y (mm)	9.50	8.00	8.00	9.00	8.00	8.00
K (kN/mm)	173.81	311.77	367.50	277.00	405.01	518.00

4. Conclusions

Despite the good performance of steel shear walls, this system has not been used at civil projects widely (because of some problems such as architect aspect requirement). In this article, an innovative model of steel shear wall was introduced, which solves the conventional SPSW's deficiency. Some of the conclusions of the numerical results can be ordered as follows:

- The base shear has reached around 80 percent of V_y in all models, but only the β_2=0.20 (DB-t3) reached around 60 percent of V_y.
- Increasing the aspect ratio (length to height) of the infill plate improves the behavior of the SPSW.
- After the occurrence of the first yield points in frame members and between the drift angles of 0.5% and 1%, the infills become less effective, and all stiffness curves merge to the open frame curve.
- Higher β_1 values increase energy absorption of the system. Also, by increasing the thickness of the infill plates, the energy absorption is enhanced, too.
- Both β_1 and β_2 are effective on the elastic stiffness. So, the elastic stiffness K is increased by raising of the β_1 and β_2 parameters.

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