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STRUCTURAL PERFORMANCE AND FAILURE ANALYSIS OF NOVEL STEEL PLATE SHEAR WALLS

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Abstract

Steel Plate Shear Walls (SPSWs) have emerged as an effective lateral load-resisting system in modern seismic engineering due to their high ductility and energy dissipation capacity. However, thin SPSWs often exhibit challenges such as premature buckling, stress concentration at frame members and plate-frame interactions, and reduced energy capacity due to earlier buckling in web plate and pinching effect in hysteretic behavior. To address these issues, this study investigates the structural performance and failure mechanisms of novel SPSWs using advanced finite element modeling in ABAQUS software. The proposed perforated designs introduce optimized openings that enhance the structural behavior by mitigating stress concentrations at frame members such as beams and columns, reducing stress at plate-frame interactions as well as controlling out-of-plane deformation. To this end, verification of the numerical model is performed against another numerical data, demonstrating strong correlation in pushover behavior and von Mises stress distribution. The study examines various novel SPSWs, including curved slots , to evaluate their effects on shear strength, initial stiffness, out-of-plane deformation, and failure modes. Finally, numerical results indicate that novel SPSWs exhibit significant improvements in out-of-plane deformation while reducing stress at frame members and plate-frame interactions.

Keywords: Novel Steel Plate Shear Walls, Pushover analysis, Structural Performance, Frame members failure evaluation.

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1 INTRODUCTION

Steel Plate Shear Walls (SPSWs) have emerged as an efficient lateral load-resisting system in modern structural engineering, particularly for seismic applications. These systems effectively absorb and dissipate seismic energy through the plastic deformation of steel, enhancing the overall stability and resilience of structures. The SPSW consists of a steel web plate enclosed by a surrounding frame of beams and columns, where plate-frame interactions and beam-to-column connections play a crucial role in load transfer [1].

SPSWs are classified based on web plate geometry into three categories: slender, semi-slender, and thick web plates. The slenderness of the web plate is defined by the ratio of its width to thickness, which influences its load-bearing mechanism. Web plates with high slenderness ratios tend to develop tension-field action as they yield, requiring the surrounding frame to be designed to effectively accommodate the redistributed stresses [2].

Thinner steel web plates tend to buckle under lower loads due to the lower buckling load, which negatively impacts the seismic energy dissipation capacity owing to the pinching effect observed in hysteretic behavior. This buckling phenomenon also induces high stress concentrations at plate-frame interactions, potentially leading to premature failure at plate-frame connections and a reduction in both shear strength and ductility. To mitigate web plate buckling in SPSWs, one common approach is the use of stiffeners. However, incorporating stiffeners presents several disadvantages, including increased construction costs, localized stress concentrations within the web plate, stiffness irregularities, and potential tearing of the web plate. These challenges necessitate alternative strategies for improving the performance of SPSWs while maintaining structural efficiency and cost-effectiveness [3].

An alternative solution to mitigate web plate buckling is the strategic introduction of openings in the steel web plate. This method enhances seismic performance by optimizing opening ratios, which increases ductility while influencing shear strength and initial stiffness. Additionally, perforations help redistribute stress more effectively and manage failure mechanisms by controlling stress concentrations. In 2005, Sabouri et al. [4] demonstrated that the shear strength and initial stiffness of the web plate decrease linearly as the diameter of a centrally located circular opening increases. However, their findings also indicated that stress tends to concentrate around the openings by buckling at the center of the steel web plate, potentially leading to localized failure near the perforations.

Incorporating novel perforation shapes in the steel web plate, such as ring-shaped openings and rectangular-linked patterns, offers several structural advantages. These designs help in reducing out-of-plane deformation and enhance seismic energy dissipation capacity by shifting the global deformation of the steel web plate to localized deformation around the links. By strategically altering the deformation pattern, this method effectively redistributes plastic hinge formation to controlled areas rather than critical zones, such as plate-frame interactions. As a result, failure mechanisms can be better managed, improving the overall resilience and performance of the SPSW system [5].

Recent research has focused on optimizing the shape of openings within the web plate to enhance structural performance. Monsef Ahmadi et al. [6] conducted a numerical study using the finite element method in ABAQUS software [7] to investigate the optimal design of steel web plates under pure shear loading. Their findings indicated that strategically reducing steel material at the center of the web plate's four sides significantly increased energy dissipation capacity and improved hysteretic behavior. Another study of Monsef Ahmadi et al. [8], examined new opening shapes in steel plate shear panels under pure shear load. The results demonstrated that for steel web plates with a slenderness ratio below 50 and thicknesses of 30 mm and 40 mm, out-of-plane deformation was significantly reduced compared to full panels. Additionally, plate-frame interactions exhibited moderate stress levels. To further minimize stress concentrations at these interactions, the authors suggested incorporating curved-shaped slots. Numerical results confirmed that web plates with curved-slot openings could halve the fracture risk at plate-frame interactions while doubling seismic energy dissipation capacity compared to a full steel web plate. It can be noted that the study employed hinge connections at beam-to-column joints to simulate pure shear loading. However, this approach disregarded the influence of the surrounding frame on the overall seismic performance of the SPSW system.

In this study, a SPSW with a rigid frame and moment-resisting beam-to-column connections was analyzed to assess the effectiveness of the proposed novel SPSWs in mitigating stress concentrations at plate-frame interactions and beam-to-column connections. To achieve this, numerical results of a SPSW were replicated using the finite element method in ABAQUS software. The findings confirmed that the numerical models accurately captured key structural parameters, including initial stiffness, shear strength, and failure mechanisms. Furthermore, the pushover curves of the proposed novel SPSWs were analyzed, offering valuable insights into their structural performance and highlighting their potential advantages in enhancing overall structural failures at the frame members and plate-frame interactions as well as controlling out-of-plane deformations.

2 FINITE ELEMENT MODEL (FEM) AND VERIFICATION PROCESS

2.1 General

In 2013, Alavi and Nateghi [9] conducted both experimental and numerical investigations on SPSWs with and without perforations. The web plate had a thickness of 0.8 mm and dimensions of 1200 mm in height and 1800 mm in width. To ensure the structural integrity and performance of SPSWs, specific design criteria must be met. The frame of the steel web plate was constructed using a rigid cross-section such as HEB160, with a moment of inertia of 24.9 $\times 10^6$ mm^4, which satisfied the required moment of inertia values specified in Equations 1 and 2 . These equations are a function of web plate thickness (t_w), height of the web plate (h) and the width of the web plate (L). These conditions ensure adequate stiffness and strength, preventing premature failure and optimizing the system's energy dissipation capacity [10].

$$I_c = 0.0031 \times \frac{t_w h^4}{L} \tag{1}$$

$$I_b = 0.0031 \times \frac{L^4}{h} \tag{2}$$

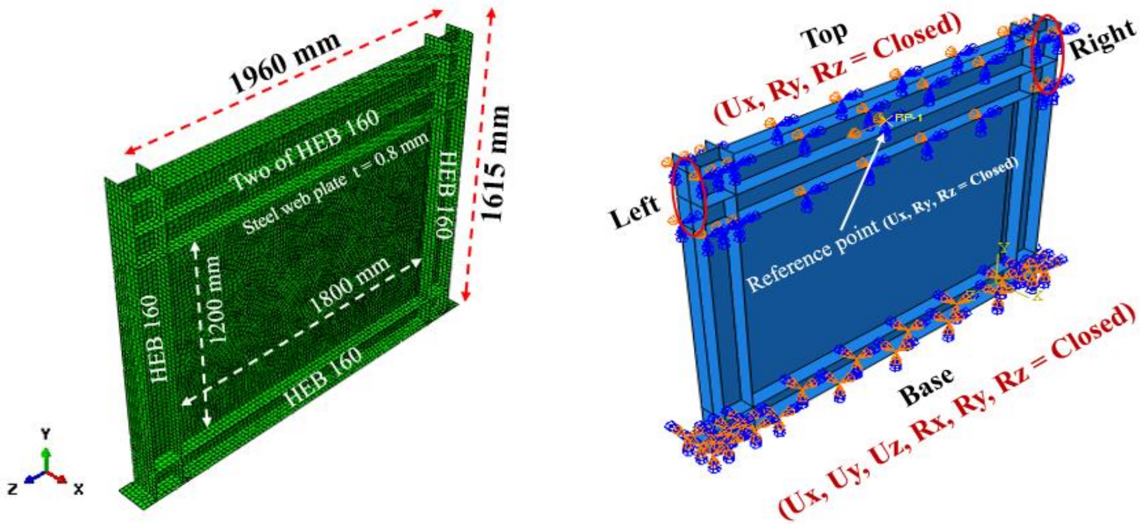
The beams and columns were connected at beam-to-column joints using full moment connections. Additionally, the steel web plate was attached to the frame through fish plates with welded connections, ensuring adequate load transfer and structural integrity.

Before conducting cyclic tests, the authors developed Finite Element Model (FEM) using ANSYS software under monotonic loading to accurately predict the behavior of the specimens, particularly in terms of stress distribution and failure capacity. Following the experimental tests, the test results demonstrated strong agreement with the numerical predictions, especially regarding stress distributions and failure based on maximum stress location.

Therefore, it can be concluded that numerical simulations serve as a valuable tool for optimizing new specimen designs within the same structural frame. These simulations enable a comprehensive evaluation of stress distribution, failure capacity, and critical seismic parameters such as shear strength, initial stiffness, and out-of-plate deformations, ultimately enhancing the understanding and performance of new types of SPSWs.

2.2 Verification Process

To replicate the numerical results established by Alavi and Nateghi [9], the FEM with same sample geometry was implemented using ABAQUS software. A fine mesh with S4R shell elements, sized at 25 mm, was selected to model the entire specimen, including the frame and the steel web plate, as shown in Figure 1a. These elements were chosen with reduced integration and hourglass control to enhance computational accuracy and efficiency.



(a) (b)

Figure 1: Finite element model (FEM) of the verification process: a) geometry and meshing, b) constrains situation of FEM.

The elastic material properties were defined based on experimental data, with the elastic modulus set at 207,000 MPa for the frame and 204,000 MPa for the steel web plate. To accurately capture the plastic behavior, the frame and plate materials were modeled using Isotropic and Combined hardening, respectively, as detailed in Table 1.

Components	Yield stress	Ultimate stress	Yield strain
	[MPa]	[MPa]	[%]
Frame members (HEB 160)	400	450	0.19
Steel web plate	280	500	0.14

Table 1: Material properties.

The boundary conditions of the numerical model for SPSW were defined as shown in Figure 1b. The base of the model was fully constrained by restricting all degrees of freedom, preventing both displacement (U) and rotation (R). To eliminate unintended out-of-plane displacements, the top of the model was restrained against movement along the x-axis (U_x) and rotations about the y- and z-axes (R_y and R_z).

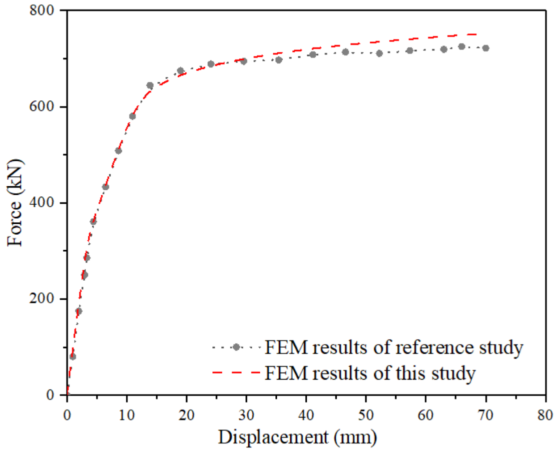
A monotonic load was applied at a reference point located at the center of the top part. This reference point was rigidly coupled to the left and right sides of the top part, ensuring uniform load distribution. All degrees of freedom displacements (U_x and U_y) and rotations (R_x, R_y and R_z) at the coupling points were constrained, except for the displacement in the z-axis (U_z), which served as the primary loading direction. The applied load followed a linear amplitude based on displacement control, progressing up to a 5% drift, corresponding to a 70 mm displacement along the z-axis.

The fishplates were explicitly modeled in the numerical specimen, with the steel web plate connected to the fishplates using a TIE-type connection to ensure modeling welded type connection at plate-frame interactions. Notably, the fishplates and beam-to-column connections were integrated into the model by merging components, resulting in a unified solid representation. This approach enhances the structural continuity and accuracy of the numerical simulation, ensuring realistic interaction between the web plate, fishplates, and surrounding frame elements.

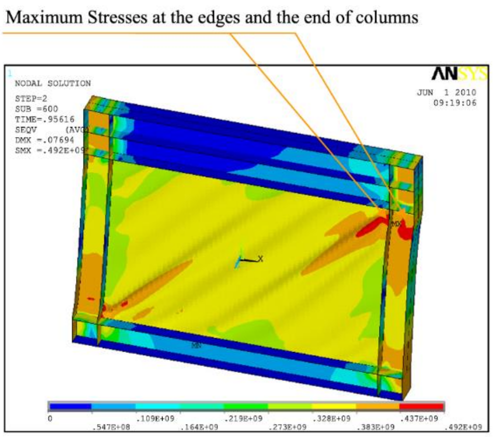
To perform the pushover analysis in the developed numerical model, a static general solution was implemented. Prior to running the analysis, a critical buckling mode was identified through linear buckling analysis to introduce minimum geometric imperfections equal to 1 mm into the model. This step ensured a more realistic representation of initial imperfections, enhancing the accuracy of the structural response prediction under lateral loading.

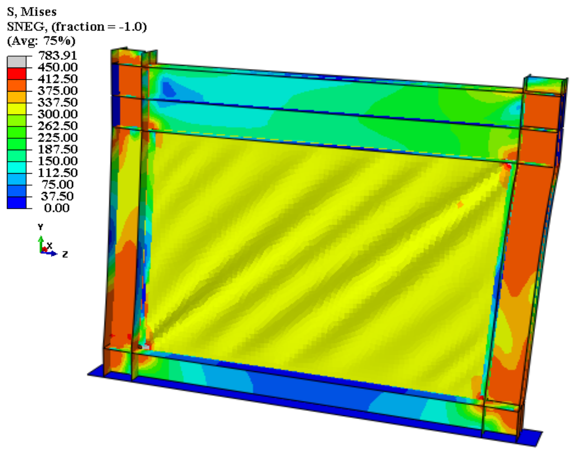
2.3 Comparing numerical results

The numerical results were compared with those from the reference study in terms of the pushover curve (Figure 2a) and von Mises stress distribution (Figures 2b and 2c).



(a)





(b) (c)

Figure 2: a) Comparing pushover curves, and von mises stress distribution in b) ANSYS software (Alavi and Nateghi) [9] and c) ABAQUS software.

Figure 2a illustrates a high degree of agreement between the numerical results obtained from ANSYS and ABAQUS. The simulation shows zero error in terms of initial stiffness, confirming the robustness of the modeling process. The maximum discrepancy—only 1%—was observed in shear strength, which can be attributed to mesh sensitivity. Additionally, the von Mises stress distributions, as depicted in Figures 2b and 2c, closely correspond between the two simulations. The minor differences noted are primarily due to the incorporation of fishplates in this study, a detail that was omitted in the reference study.

These findings confirm that the numerical simulations performed using ABAQUS software provide a reliable representation of the structural behavior of SPSWs. Therefore, this modeling approach can be effectively utilized in future studies on novel SPSW designs.

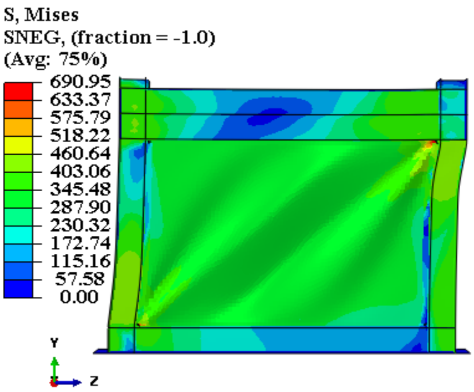
3 STRUCTURAL PERFORMANCE AND FAILURE EVALUATION

3.1 General

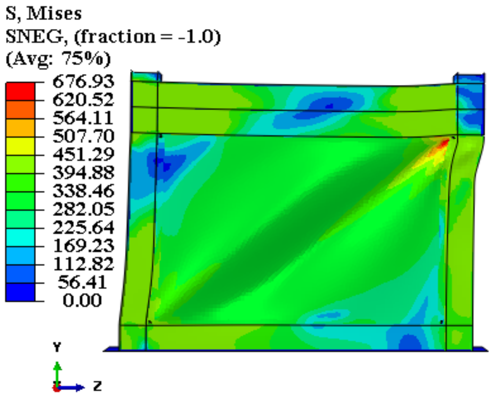
This subsection introduces various types of novel SPSWs featuring innovative cut-out designs. The primary objectives of incorporating these perforations are to optimize stress distribution at frame members by controlling out-of-plane deformation of steel web plates, mitigate fracture risk in the main frame such as beams and columns, and enhance fracture capacity of plate-frame interactions. To achieve these goals, the numerical model presented in the previous subsection is employed, maintaining the same frame dimensions, material properties, mesh sizes, and analysis method by means of ABAQUS software. All numerical specimens are subjected to lateral loading up to 5% drift, and their structural performance is evaluated based on initial stiffness, maximum shear strength, yield strength, out-of-plane deformation and fracture capacity.

3.2 Pushover analysis of full SPSWs

Full SPSWs with increased web plate thickness and reduced slenderness impose significant stress on the main frame components, including beams and columns. To accommodate the transferred stresses from the steel web plate, these structural members must be designed to meet the minimum requirements specified in Equations 1 and 2 for columns and beams, respectively. Failure to do so may result in excessive deformation of the beams and columns. To illustrate this phenomenon, the same numerical model is utilized as explained in section 2, considering web plate thicknesses of 4 mm and 8 mm to analyze failure capacity within the main components. The von Mises stress distribution for both full SPSWs is presented in Figure 3. As expected, decreasing the slenderness of the web plates leads to increased stress concentrations in the frame members, thereby elevating the risk of buckling and the likelihood of failure in the beams and columns as shown in Figures 3a and 3b.



(a)



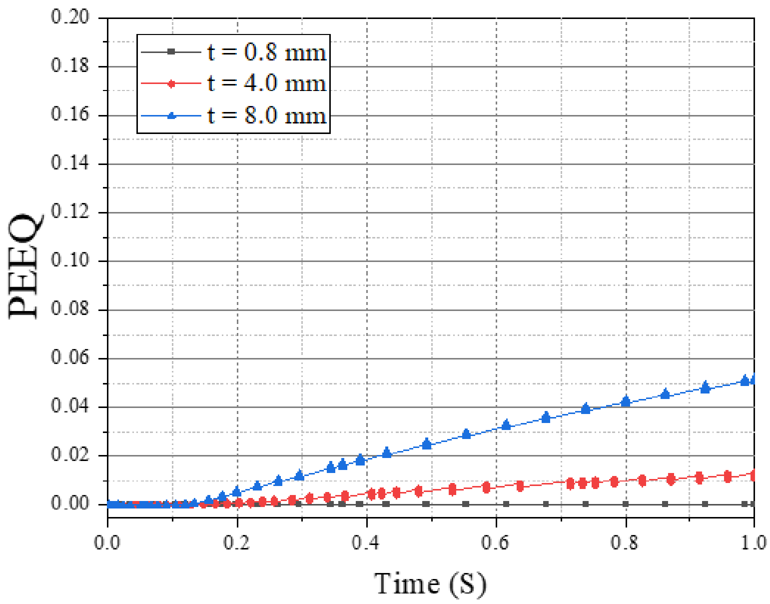
(b)

Figure 3: von Mises stress distribution in full SPSWs with steel web plate equal to: a) 4 mm and b) 8 mm.

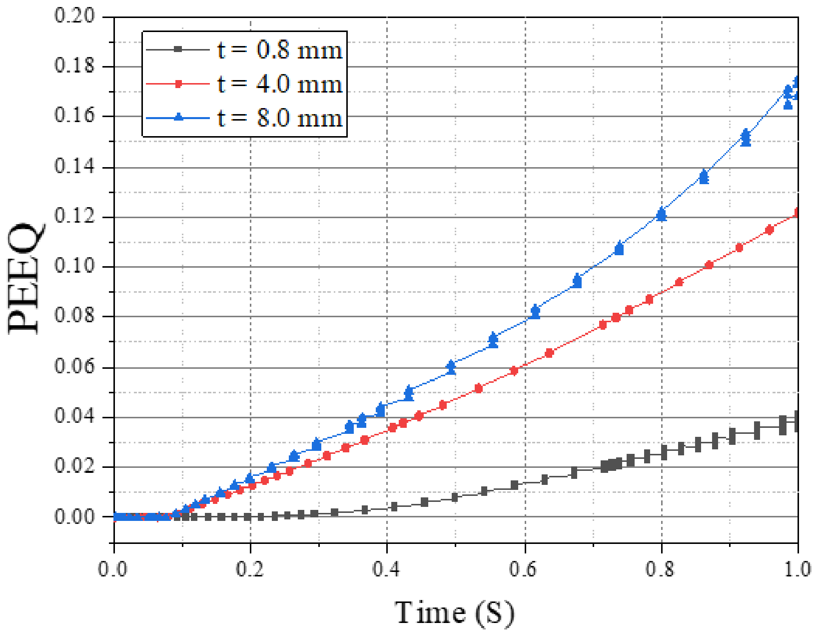
The failure of SPSWs in the FEM can be estimated using the equivalent plastic strain (PEEQ), which is calculated as shown in Equation 3. Here $\bar{\varepsilon}^{Pl}|_0$represents the initial equivalent plastic strain, and $\dot{\varepsilon}^{pl}$ denotes the equivalent plastic strain rate.

$$\bar{\varepsilon}^{Pl}(PEEQ) = \bar{\varepsilon}^{Pl}|_0 - \int_0^T \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl}:\dot{\varepsilon}^{pl}}dt \tag{3}$$

The PEEQ values of three SPSWs with different web plate thicknesses (0.8 mm, 4 mm, and 8 mm) are compared at the critical zones of the beam and columns. Figures 4a and 4b illustrate the equivalent plastic strain distribution in these frame components, highlighting their structural response



(a)



(b)

Figure 4: PEEQ values in frame components a) Beam and b) Columns.

As shown in Figure 4, the PEEQ values increase as the web plate slenderness decreases in both the beam and column. The maximum PEEQ value in the column exceeds that of the beam, primarily because both components share the same cross-sectional profile. However, as indicated in Equation 1, the column must be designed to be stronger than the beam when SPSWs are constructed with a full steel web plate to ensure structural integrity. Additionally, the results confirm that the SPSW with a 0.8 mm steel web plate thickness, as well-designed in the reference study, exhibited the lowest PEEQ values in both the beam and column. Experimental findings further validated that, at this PEEQ level, the beams and columns remained completely safe without any failure. Therefore, it can be concluded that a PEEQ value below 0.05 in both beams and columns with cross-section as HEB160 ensures SPSW safety without failure.

3.3 Pushover analysis of novel SPSWs

In the previous study, the authors of this study proposed a novel SPSWs with optimized design cut-outs to control out-of-plane deformation and enhance the structural performance of SPSWs under cyclic pure shear loading. The results indicate that the suggested novel SPSWs effectively prevent out-of-plane deformation, thereby eliminating the pinching effect in hysteretic behavior and increasing energy dissipation capacity. On the other hand, incorporating curved shape slots into these novel SPSWs provides engineers with a range of design parameters, enabling them to tailor the panels to meet specific performance requirements. However, the impact of these novel SPSWs including curved shape slots on the failure mode of the frame members such as beam and columns has not yet been investigated. Therefore, this study aims to evaluate the effectiveness of these novel SPSWs on the stress distribution and failure behavior of the main frame members and plate-frame interactions.

The geometry of novel SPSWs is illustrated in Figure 5. The numerical specimens are categorized into four groups: full SPSWs (SPSW-t), novel SPSWs (N-SPSW-t) and novel SPSWs with curved slots (N-SPSW-C-t), As referenced [6], the web plate thickness is selected as either 30 mm or 40 mm to prevent complete out-of-plane displacement and enhance energy capacity of novel SPSWs. It is important to note that the web plate thickness is denoted by “t” in the specimen names.

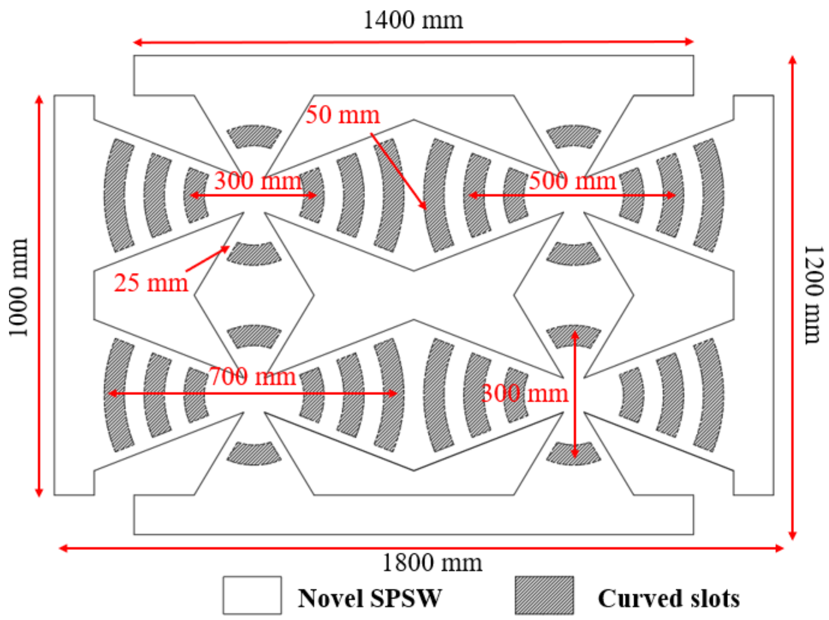


Figure 5: Design parameters of the Novel SPSWs.

3.4 Structural performance of numerical specimens

The structural performance of the numerical specimens: SPSW - 0.8, SPSW - 4, SPSW - 8, N-SPSW - 30, N-SPSW - 40, N-SPSW-C-30 andN-SPSW-C-40, is evaluated in terms of maximum force (F_{max}), yielding force (F_y), initial stiffness (k), and out-of-plane displacements (U_x), as shown in Table 2. The maximum load is recorded the maximum force value in push-over curves. The yielding force is determined using a bilinearization method as described in FEMA 273. Initial stiffness is calculated as the ratio of the yielding force to the yielding displacement (Δ_y).

N	$Specimens$	$F_{max}(kN)$	$F_y\ (kN)$	Δ_y (mm)	$k\ (kN/mm)$	$U_x\ (mm)$
1	$SPSW-0.8$	752.7	546.0	9.6	56.9	19.2
2	$SPSW-4$	1467.2	1203.7	6.5	185.1	50.9
3	$SPSW-8$	2211.9	2016.0	4.2	480.0	82.8
4	$N-SPSW-30$	2275.1	1678.0	9.2	182.4	4.9
5	$N-SPSW-40$	2742.5	2085.1	10.7	194.9	2.3
6	$N-SPSW-C-30$	1571.1	893.4	7.2	124.1	3.9
7	$N-SPSW-C-40$	1904.6	1073.0	6.7	160.1	1.5

Table 2: Structural performance of numerical specimens.

As shown in Table 2, increasing the web plate thickness results in higher maximum force and yielding force as well as initial stiffness across all categories. In the SPSW-t specimens, yielding displacement significantly decreases as the web plate thickness increases. In contrast, the other categories exhibit only slight variations in yielding displacement with changes in web plate thickness. This difference is attributed to the tension field action in the SPSW-t specimens, which promotes earlier yielding of the web plate. In the other categories, the special opening shapes facilitate stress transfer into the web plate, thereby mitigating significant changes in yielding displacement. Moreover, the lowest initial stiffness values were observed in specimens with openings at the plate-frame interactions, indicating that openings at these interfaces markedly diminish structural performance.

In terms of out-of-plane displacement U_x, all numerical specimens—with the exception of the SPSW-t category—demonstrated significant improvements. To quantify the influence of increasing web plate thickness on out-of-plane displacement, normalized ratios are calculated. In each column, a value of 1.0 represents the baseline normalized out-of-plane displacement for the corresponding row. Table 3 presents these normalized values, with specimen numbers corresponding to those in Table 2. Moreover, these normalized matrices offer engineers valuable insights into how the proposed perforated steel plate design can effectively replace a full steel web plate. It is important to note that each matrix cell is read by column and row; for example, the value in the 3×5 cell represents the ratio of the out-of-plane displacement of specimen 3 to that of specimen 5.

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	1.00	0.38	0.23	3.92	8.35	4.92	12.80
2	2.65	1.00	0.61	10.39	22.13	13.05	33.93
3	4.31	1.63	1.00	16.90	36.00	21.23	55.20
4	0.26	0.10	0.06	1.00	2.13	1.26	3.27
5	0.12	0.05	0.03	0.47	1.00	0.59	1.53
6	0.20	0.08	0.05	0.80	1.70	1.00	2.60
7	0.08	0.03	0.02	0.31	0.65	0.38	1.00

Table 3: Normalized out-of-plane displacement.

As shown in Table 3, the highest value is observed in cell 3×9, which corresponds to the lowest value in cell 9×3. This indicates that, among specimens in the third category, those with higher web plate thickness exhibit the lowest out-of-plane deformation compared to full SPSW specimens with the maximum web plate thickness. Furthermore, Table 3 confirms that the proposed novel SPSWs—as detailed in the reference study—is effective in restraining buckling phenomena. This improved performance is attributed to the successful redistribution of global buckling deformation into the created links, where local buckling subsequently occurs.

3.5 Failure performance

The failure performance of frame components—specifically beam and columns—is evaluated using PEEQ values for all categories of numerical specimens with web plate thicknesses of 40 mm and 4 mm, as illustrated in Figure 6. In Figure 6a, the SPSW-4 specimen shows elevated PEEQ values at the column and plate-frame interactions, indicating a higher likelihood of failure. In contrast, the N-SPSW-40 andN-SPSW-C-40, specimens exhibit generally lower PEEQ values, as depicted in Figures 6b and 6c, , respectively. Notably, incorporating curved slots significantly reduces the formation of plastic hinges in both the frame components and the plate-frame interactions.

Furthermore, Figure 7 compares the maximum PEEQ values in the columns of the frames for the N-SPSW-t and N-SPSW-C-t, specimens, with these values normalized by the out-of-plane deformation observed in the SPSW-t category. The results indicate that increasing the web plate thickness leads to the reducing the PEEQ values seen in columns of the frame of novel SPSWs. Based on these numerical results, it can be concluded that the proposed novel

SPSWs with curved slots is an effective solution for mitigating the formation of plastic hinges in critical frame components such as beams, columns, and plate-frame interactions.

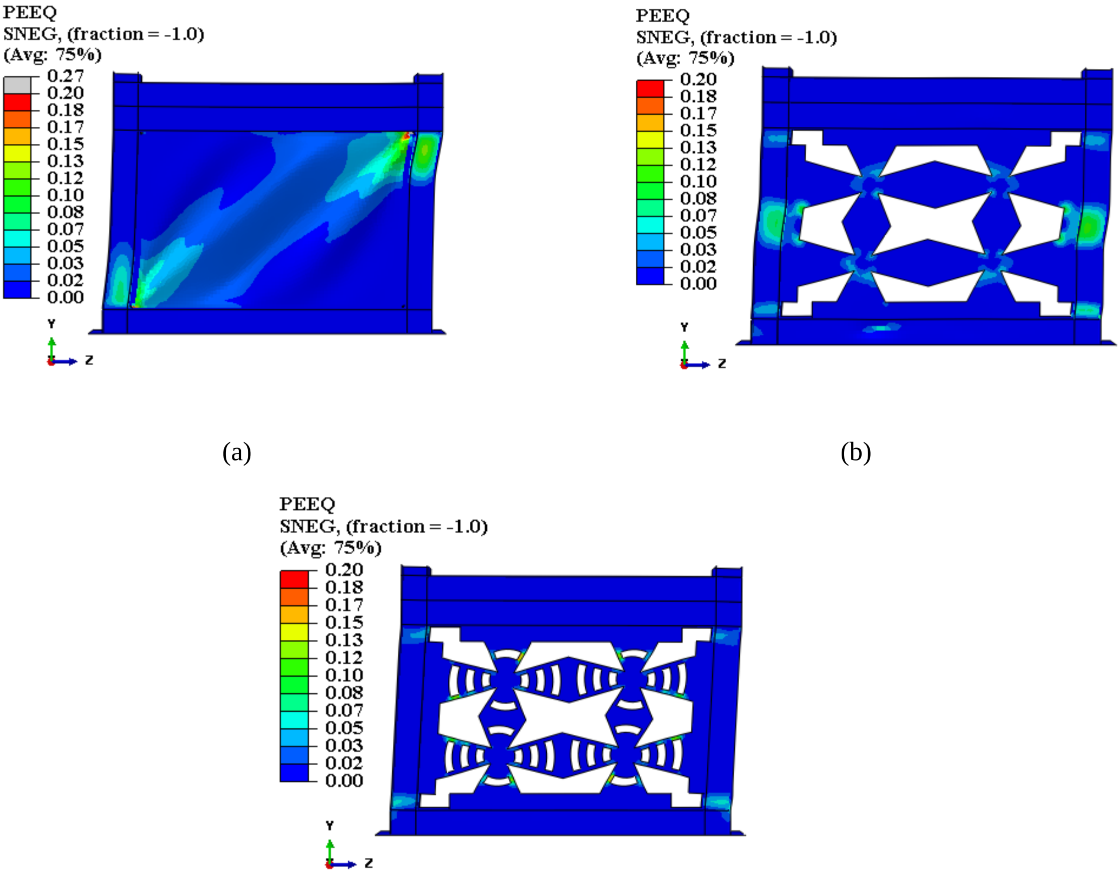


Figure 6: Maximum PEEQ values in a) SPSW-4, b) N-SPSW-40 and c) N-SPSW-C-40.

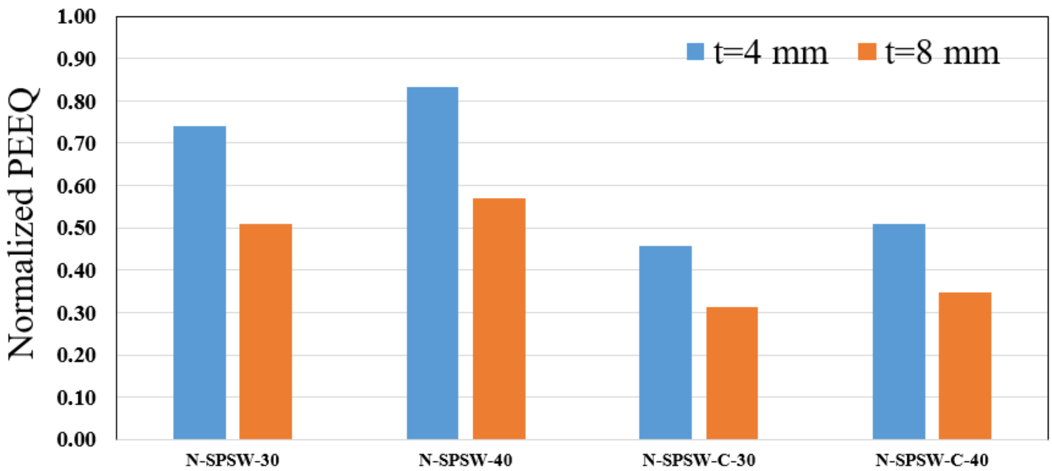


Figure 7: Normalized PEEQ values of novel SPSWs with full SPSWs.

4 CONCLUSION

This study demonstrates the significant potential of novel steel plate shear walls (SPSWs) to enhance both seismic performance and failure resistance. Numerical simulations—cross-validated with alternative datasets—indicate that increasing web plate thickness improves yielding force, initial stiffness, and overall load capacity. In contrast, conventional specimens tend to concentrate stress in critical regions, thereby elevating the risk of plastic hinge formation in the frame components. Moreover, the introduction of strategic openings in the steel web plates—particularly designs featuring curved slots—substantially mitigate out-of-plane deformations and reduces the development of plastic hinges at both the plate-frame interfaces and within key structural elements such as beams and columns. Normalized performance metrics further confirm that these design modifications promote effective stress redistribution within the web plate by converting global buckling phenomena into localized buckling, ultimately reducing the likelihood of failure.

Collectively, these findings suggest that the proposed novel SPSW configurations, especially those incorporating curved slot patterns, offer a promising alternative to traditional steel web plates. They not only maintain structural integrity under horizontal loads but also provide engineers with enhanced design flexibility to optimize performance and safety.

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