Civil Engineering and Applied Solutions

Research Article

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Finite Element Investigation of Stiffened Beam-Only Connected Steel Plate Shear Walls under Cyclic Loading

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ARTICLE INFO

Article history:

Received 07 February 2026

Revised 29 April 2026

Accepted 06 June 2026

Available online 01 January 2027

Keywords:

Steel plate shear wall

Stiffener

Nonlinear analysis

Finite element method

Cyclic behavior

Dissipated energy

ABSTRACT

This study investigates a novel type of steel plate shear wall (SPSW) system in which the infill plate is detached from the boundary columns and reinforced using side, horizontal, or cross stiffeners. Although conventional SPSW systems offer several advantages, their main drawback is the requirement for large column sections due to the significant tension field forces developed in the infill plate after buckling. According to the capacity design concept, boundary columns must resist these forces to prevent the formation of plastic hinges along the column height. In recent years, the concept of separating the steel plate from the boundary columns has been proposed to mitigate these demands. In this study, the behavior of stiffened beam-only connected steel plate shear walls (BO SPSWs) is investigated using finite element analysis. The effects of stiffener arrangement, stiffener cross section, stiffener dimensions, and web plate thickness are examined. The numerical results demonstrate stable cyclic responses with no sudden strength degradation, indicating the ductile and reliable behavior of the proposed system. For configurations with side, horizontal, and cross stiffeners, tension fields develop within the steel plate, forming between the stiffeners and boundary beams and within the resulting subpanels. Among the investigated stiffener sections, T-shaped stiffeners provide superior structural performance. Furthermore, increasing the stiffener dimensions and the web plate thickness leads to higher ultimate strength and improved energy dissipation capacity.

How to cite this article: Meghdadi, Z., Shabanlou, M. Mofid, M. Finite Element Investigation of Stiffened Beam-Only Connected Steel Plate Shear Walls under Cyclic Loading. Civil Engineering and Applied Solutions. 2027; 3(1): 131–145. doi:10.22080/ceas.2026.31223.1077.

1. Introduction

In recent decades, the Steel Plate Shear Wall (SPSW) system has become one of the main lateral load-resisting systems in modern construction projects due to its inherent high stiffness, ductility, and redundancy, as well as stable cyclic behavior. While unstiffened SPSWs are more prevalent in the United States, stiffened SPSWs are mainly preferred in Japan, located in a high seismic area [1, 2]. Compared to concrete shear walls, this system is more easily erected and occupies less space, which makes it suitable for architectural purposes. Despite the mentioned advantages, the main drawback of this system is the large column sections needed for resisting the lateral forces imposed on the boundary columns resulting from the tension field formed in the steel plate. In addition, the section of the column depends on the thickness of the web plate, making it hard to satisfy the drift demands [3, 4].

Elgaaly et al. [5] performed cyclic tests on six unstiffened SPSW systems. The results showed that the behavior of an unstiffened SPSW system with thin and thick web plates is mainly governed by the yielding of the plates and columns, respectively. Ghosh et al. [6]proposed a performance-based design framework for unstiffened SPSW systems based on inelastic drift demands by performing a test on a four-story building. The cyclic tests of four two-story narrow SPSWs performed by Li et al. [7], Li et al. [8]

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https://doi.org/10.22080/ceas.2026.31223.1077
ISSN: 3092-7749/

showed that the capacity design method could guarantee the formation of plastic hinges at the bottom of the first-story column.

Numerous solutions have been proposed to decrease or eliminate the tension field forces imposed on boundary columns. For instance, Roberts and Sabouri-Ghomi [9] were the first to investigate the behavior of perforated steel shear panels by performing a series of quasi-static experiments on steel shear panels with circular openings in the center of the panel. The results showed good s-shape hysteretic behavior with satisfying ductility. Purba and Bruneau [10] conducted finite element monotonic pushover analyses to study the behavior of perforated SPSWs with multiple circular openings in a regular pattern. As a result, they suggested a formulation for estimating the shear strength of this system as a function of perforation diameter, the distance between perforations, and the shear strength of the solid panel. Chan et al. [11] recommended using perforated steel web plates to reduce the forces imposed on the boundary elements. Valizadeh et al. [12]studied the behavior of perforated SPSWs by performing experiments on eight one-story, one-bay specimens. Bahrebar et al. [13]investigated the behavior of curved-corrugated SPSWs with perforations by conducting nonlinear finite element analysis on 128 models. Ahmad Khan and Srivastava [14] have comprehensively studied the effect of different shapes, sizes, and locations of openings in unstiffened SPSWs by performing finite element analyses on 98 models.

Another alternative for reducing tension field forces found in the steel plate is to use Low Yield Steel (LYS) for web plates. Vian et al. [15] conducted four experiments on LYS SPSW specimens in which two of the panels were solid, and the other two were perforated. The results showed that the LYS web plate could be used to efficiently design boundary elements. Chen and Jhang [16] proposed a design method for LYS SPSWs by performing cyclic tests on five specimens considering the beam-to-column connections detailing and the width-to-thickness ratio of steel plates.

For the main purpose of postponing the buckling of the infill plate, the installation of concrete panels has been proposed. Astaneh-Asl [17] presented a report on seismic behavior and design of steel plate shear walls covered by reinforced concrete panels. Zhao and Astaneh-Asl [18] performed cyclic tests on three-story specimens of composite SPSW systems. The concrete panels were bolted to the steel web plates with a gap between the concrete panels and boundary elements, which reacted adequately ductile and exhibited stable cyclic behavior. Arabzadeh et al. [19] experimentally studied one-story and three-story specimens. They found that the bolt spacing to plate thickness ratio is positively correlated with system ductility, while the plate yield point is negatively correlated with this ratio.

Also, using corrugated steel plates not only postpones the buckling of the infill plate but also provides more energy dissipation capacity. Emami and Mofid [20], Emami et al. [21] conducted a series of experimental studies on unstiffened and trapezoidally corrugated SPSWs. They showed that although the ultimate strength of the unstiffened SPSW is higher than that of corrugated SPSWs, the energy dissipation capacity of corrugated SPSWs is much greater. Farzampour et al. [22] studied the behavior of corrugated SPSWs with and without openings by performing finite element analysis on 540 numerical models that resulted in proposing an ultimate strength prediction procedure. Hosseinzadeh et al. [23] studied the effect of the trapezoidal plate angle on the performance of corrugated SPSW. The results showed that the stiffness and energy dissipation of the corrugated SPSW are adverse to the trapezoidal plate angle.

Another solution for preventing the web plates from premature elastic buckling is installing stiffeners on either one face or both faces of the web plate. Using more stiffeners results in higher energy dissipation capacity. In addition, stiffeners reduce out-of-plane deformation of web plates and prevent global buckling, leading to extensive yielding in the web plate. Alinia [24] investigated the behavior of stiffened steel plates by conducting 1200 finite element analyses. The results showed that the optimum arrangement of stiffeners in fully connected SPSWs is determined such that the critical stress of subpanels does not exceed the yield stress. Besides, the stiffeners are most effective when they change the global buckling mode of SPSW to local buckling mode in subpanels. Alinia and Dastfan [25] numerically investigated the cyclic behavior of stiffened SPSWs and figured out that while unstiffened SPSWs have high ductility, the stiffened SPSWs have high energy dissipation capacity and suggested an optimized stiffening ratio. Alinia and Sarraf Shirazi [26] also proposed procedures for designing stiffeners with optimum dimensions. Sabouri-Ghomi and Sajjadi [27] experimentally studied the behavior of SPSWs and verified the plate-frame interaction theory.

Guo et al. [28] investigated the effects of joint properties classified as hinged, rigid, and semi-rigid connections on the behavior of unstiffened and stiffened SPSWs. It is concluded that the semi-rigid connections perform very well within the frame of SPSW systems. Also, Guo et al. [29] experimentally investigated the behavior of cross-stiffened SPSWs with semi-rigid frame connections, which benefit from a much easier type of construction. The specimens showed highly ductile behavior and great energy dissipation capacity. Ma et al. [30] presented a novel buckling-restrained multi-stiffened low-yield-point SPSW. The experimental results indicated that the suggested system complies with the limitations of available design codes.

Several studies have been carried out to eliminate the tension field forces imposed on boundary columns by separating the web plate from the vertical boundary elements. The survey of Beam-Only connected Steel Plate Shear Walls (BO-SPSW) began in the early 1990s by Xue and Lu [31]. Choi and Park determined the inclination angle of the partial tension field by conducting experiments on three-story BO-SPSWs. Furthermore, the results showed that while the deformation capacity of BO-SPSW is equal to that of a fully-connected SPSW, its load-bearing capacity is lower [32]. Guo et al. [33] tested BO-SPSWs with and without secondary columns. The experiments illustrated that using secondary columns doesn't significantly affect the ultimate strength but increases the energy dissipation capacity.

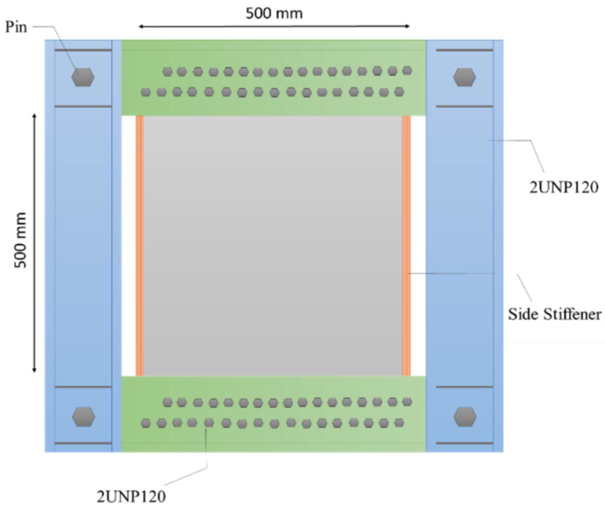
Clayton et al. [34], Ozcelik and Clayton [35] proposed to connect the web plates only to horizontal boundary elements to diminish the web plate damage. The experimental results showed that this detailing could effectively reduce and postpone the initiation of the tear in the web plate. Yet, it is essential to use larger plate thicknesses to provide enough load-bearing capacity equal to that of a fully-connected SPSW [34, 36]. Rong et al. [37] investigated the use of concrete panels on the face of BO-SPSW, which prevents the infill plate from out-of-plane buckling and increases the ductility capacity as well as the energy absorption of the composite SPSW. Ozcelik and Clayton [38] proposed a new strip model used in the macro-modeling of BO-SPSWs based on the partial tension field formed in web plates.

Shekastehband et al. [39] experimentally studied the behavior of beam-only connected perforated and solid SPSWs with secondary columns. Shekastehband et al. [40] also investigated the behavior of Low Yield Strength (LYS) and High Yield Strength (LYS) BO-SPSWs. The experimental results revealed that, as the HYS specimen was more vulnerable to web plate failure in connections when compared to the LYS specimen, it showed higher strength degradation. However, HYS steel can be used to compensate for the reduced strength of BO-SPSWs. Ozcelik and Clayton [41] studied the behavior of columns in BO-SPSW systems. As separating the SPSW from the columns can result in unequal drifts of columns, the instability of columns in BO-SPSWs is expected. As a result, an equation is proposed for a reduction factor of column buckling strength. Other experimental and numerical studies have investigated the behavior of BO-SPSWs with different construction details and materials that are not discussed herein for the sake of brevity [42-44].

The stiffness, strength, and energy absorption capacity of BO-SPSWs were investigated in previous research. As the literature lacks the investigation of stiffened BO-SPSWs, this study aims to capture the structural performance of stiffened BO-SPSWs with different web plate thicknesses and various arrangements along with the sections of stiffeners included. To this end, the unstiffened BO-SPSW of Guo et al. [33] was selected, and numerical studies were conducted by varying the arrangement and sections of stiffeners in different web plate thicknesses.

2. Characteristics of the BO-SPSW specimens

This study investigates the structural performance of stiffened BO-SPSWs with different construction details using the finite element method by analyzing fifteen specimens in three main categories, as illustrated in Fig. 1 The varying parameters in this study are the web plate thickness, arrangement, and sections of stiffeners, as tabulated in Table 1 Furthermore, the dimensions and slenderness ratio of subpanels and their critical stress are controlled according to previous research and design codes [3, 45]. Also, the dimensions of stiffeners are controlled to meet the weldability requirements based on AASHTO specifications [46].



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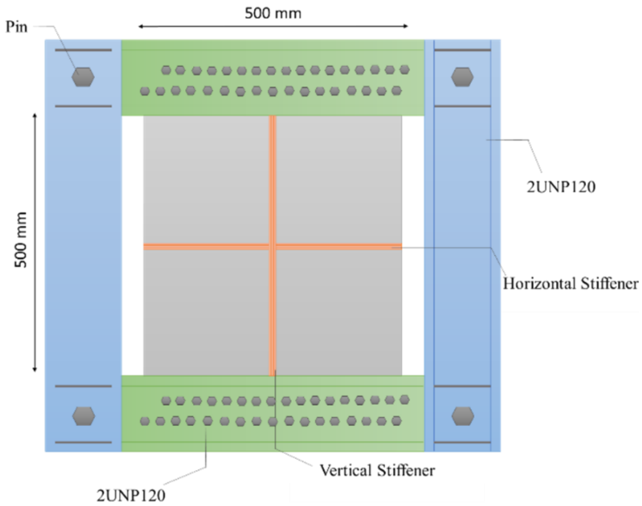

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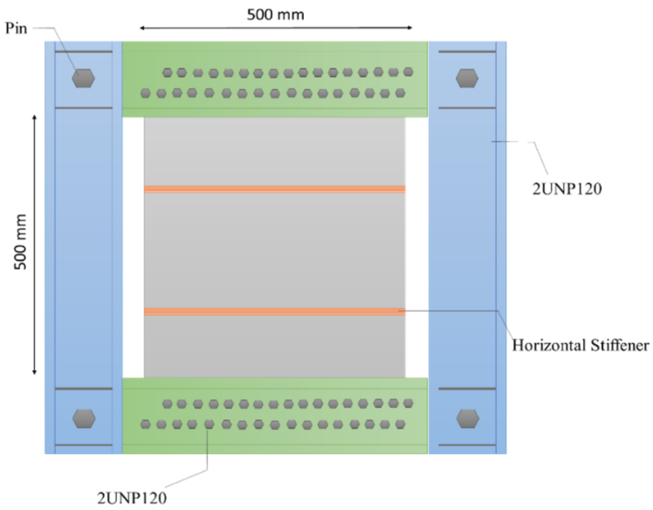


(c)

Fig. 1. Details of the BO-SPSW modeled specimens in three main categories: (a) Side-stiffened (b) Cross-stiffened and (c) Double-horizontally stiffened.

Table 1. Details of the stiffened BO-SPSW models.

Specimen Name	Stiffener Section	Web Plate Thickness
SSt1T20	T20x20x2	0.4 mm
SSt2T20	T20x20x2	0.8 mm
SSt3T20	T20x20x2	2 mm
SSt2T30	T30x30x3	0.8 mm
SSt2B20	B20x20x1	0.8 mm
CSt1T20	T20x20x2	0.4 mm
CSt2T20	T20x20x2	0.8 mm
CSt3T20	T20x20x2	2 mm
CSt2T30	T30x30x3	0.8 mm
CSt2B20	B20x20x1	0.8 mm
DHSt1T20	T20x20x2	0.4 mm
DHSt2T20	T20x20x2	0.8 mm
DHSt3T20	T20x20x2	2 mm
DHSt2T30	T30x30x3	0.8 mm
DHSt2B20	B20x20x1	0.8 mm

The details of the specimens are tabulated in Table 1. Each name tag provides information about the details of a specimen; for example, SS, CS, and DHS stand for side, cross, and double-horizontal arrangement of stiffeners, respectively. In addition, t1, t2, and t3 represent the different thicknesses of web plates equal to 0.4 mm, 0.8 mm, and 2 mm, respectively. Also, Taxbxc and Baxbxc stand for T-shape and box-section stiffeners in which a, b and c represent the width, height, and thickness of the stiffener, respectively.

3. Finite element modeling and verification

A finite element model is developed using a continuum web plate model to clearly represent the tension field that emerged in the single-bay single-story stiffened beam-only connected steel plate shear wall. In cases where extremely high ductility and redundancy are not needed, SPSWs with simple beam-to-column connections are a proper ideal system. Also, the tension field formed in the infill plate of SPSWs in simple frames is presumed to be uniform [47].

In many practical lateral load–resisting systems, such as frames with braces or steel plate shear walls, the beam–column connections in the bays containing these systems are typically detailed as pinned connections. Under such configurations, the gravity frame in the SPSW bay contributes minimally to the overall lateral stiffness, and the primary resistance to lateral loads is provided by the wall or bracing system. In this study, the boundary frame in the SPSW bay is therefore modeled as a pinned frame, consistent with these common design practices. Moreover, this modeling approach allows a focused assessment of the behavior of web plates in stiffened BO-SPSWs, where the frame action does not take part in lateral load resistance [38, 41, 48]. Besides, the boundary frame bases are pinned, and the frame is restrained against out-of-plane displacement.

The stiffened BO-SPSWs are modeled using a finite element software developed at Sharif University of Technology by Khoei et al. [49] [50, 51]. There are various methods for modeling the infill plate of SPSW systems, including a tension-only strip model [3], tension-compression strip model [52], and shell element. Although shell element modeling has the highest computational cost among the other methods, it provides high accuracy, especially when there are strain concentration and localized stress in the web plate [53]. The elements used for modeling the web plates and stiffeners are four-noded shell elements with reduced integration. Moreover, the beams and columns are modeled as very stiff line elements using three-dimensional beam elements. To ensure the adequacy of the finite element discretization, a mesh sensitivity analysis was conducted for the web plate elements. Four different mesh sizes (40 × 40 mm, 30 × 30 mm, 25 × 25 mm, and 20 × 20 mm) were examined, and their influence on key response parameters was evaluated. The comparison focused on initial stiffness, ultimate strength, and overall hysteretic response characteristics. The results showed that reducing the mesh size from 40 mm to 30 mm led to noticeable changes in the predicted ultimate strength (approximately 6%) and initial stiffness (about 5%). However, further refinement from 30 mm to 25 mm resulted in differences of less than 2% in ultimate strength and less than 2.5% in initial stiffness. Refinement from 25 mm to 20 mm produced negligible changes (below 1%) in global response parameters, while significantly increasing computational time. In addition to global response quantities, the 25 × 25 mm mesh was verified to adequately capture localized buckling modes and strain concentration patterns in the stiffened web panels, with no meaningful change in buckling shape observed upon further refinement. Therefore, a mesh size of 25 × 25 mm was adopted as an optimal compromise between numerical accuracy and computational efficiency for web plate elements. Also, the sections of beams and columns are chosen as double UNP120. The bolted connection between the web plate and boundary beams is modeled using a tie constraint.

The bilinear hardening steel material based on the true stress-strain curve data is used for modeling the web plate and the materials of stiffeners [54, 55]. This material model incorporates isotropic strain hardening and is capable of reproducing the primary yielding and post-yield stiffness characteristics of structural steel under cyclic loading. The von Mises yield criterion was adopted to simulate the onset of yielding. In contrast, the boundary beams and columns were modeled using linear elastic steel material, as their behavior remained essentially within the elastic range in the present study. It should be noted that an explicit combined hardening model including calibrated kinematic and isotropic hardening parameters was not employed. The adopted bilinear model was considered adequate for capturing the global cyclic response, overall hysteretic behavior, and energy dissipation capacity of the system, which constitute the primary objectives of this study. However, potential cyclic degradation effects such as low-cycle fatigue and detailed cyclic hardening/softening phenomena are not explicitly modeled and may influence the response under very large inelastic deformations. Here, the yield stress of the steel material is considered 300 MPa. The Young's modulus of elasticity and Poisson's ratio are presumed to be E = 200 GPa and 0.3, respectively. Besides, the von Mises yield criterion is utilized as the failure criterion.

The web plates are not perfectly flat due to fabrication tolerances and construction-related geometric irregularities. Therefore, in order to capture the shear buckling behavior of the web plates, an initial geometric imperfection was introduced into the numerical models. The imperfection shape was defined as a linear combination of the first five buckling modes obtained from an eigenvalue buckling analysis, with a maximum amplitude equal to H/1000, where H represents the plate height. This imperfection magnitude has been widely adopted in numerical simulations of steel plate shear walls and thin steel plates, as it provides a realistic representation of typical fabrication tolerances while preventing unrealistically large geometric deviations [56]. In addition, employing a combination of several buckling modes allows a more representative initial imperfection pattern compared with a single-mode imperfection and improves the ability of the model to capture the interaction of local buckling shapes and the subsequent tension field development in the web plate during cyclic loading. Both material and geometrical nonlinearities of stiffened BO-SPSWs are considered in the analyses, and the models are cyclically loaded at the top corner of the frame according to the SAC loading protocol, which is depicted in Fig. 2 [57].

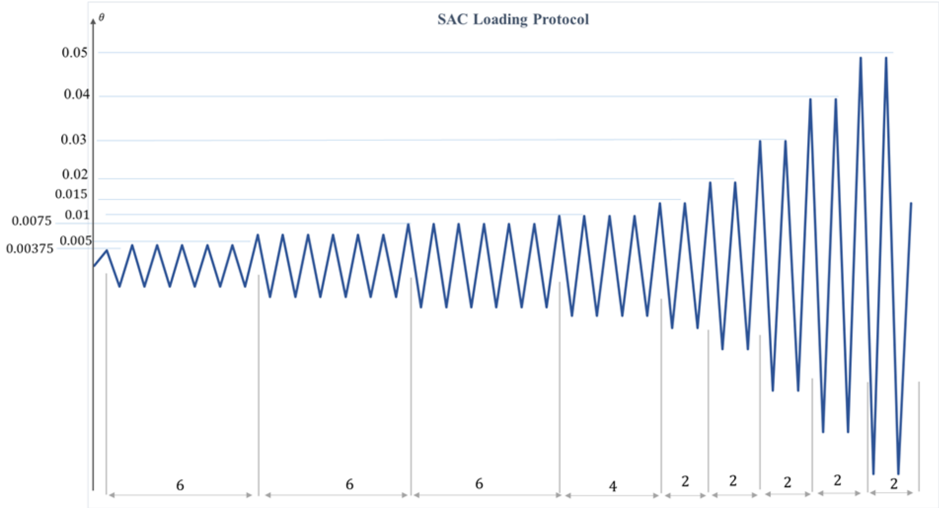


Fig. 2. SAC loading protocol.

It should be noted that, to the best of the authors' knowledge, experimental research on beam-only connected steel plate shear walls is very limited, and no experimental data are currently available for stiffened BO-SPSW specimens. Therefore, in order to validate the accuracy of the finite element modeling, a verification analysis is conducted based on the 1/3 scale one-story one-bay experimental specimen tested by Guo et al. [33]. The analysis results indicated good agreement with experimental results as depicted in Fig. 3 and Fig . 4 The envelope curves indicate that the maximum lateral strength obtained experimentally is approximately 210 kN in the positive loading direction and about 220 kN in the negative direction. The corresponding numerical predictions are approximately 200 kN (positive) and 203 kN (negative). Accordingly, the discrepancy in peak strength is about 4–5% in the positive direction and 7–9% in the negative direction, demonstrating good agreement. The initial elastic stiffness, estimated from the slope of the load–displacement response within the first loading cycle, is also closely captured. The numerical model slightly overestimates the initial stiffness by approximately 5–7%, which may be attributed to unavoidable experimental factors such as minor slip, connection flexibility, and residual imperfections not fully represented in the model. The yield point, identified from the deviation of linearity in the backbone curve, occurs at approximately 150–160 kN experimentally and 145–155 kN numerically, resulting in a difference of less than 5%. Furthermore, the numerical model successfully reproduces the stable hysteresis loop shape observed experimentally, including absence of significant pinching, gradual stiffness degradation with increasing drift, and stable strength development up to ±40 mm displacement. The cumulative energy dissipation capacity, inferred from the relative area enclosed by the hysteresis loops at large displacement amplitudes, shows comparable magnitude between the two responses, with only minor underestimation in the numerical model due to slightly lower peak loads. Overall, the small discrepancies observed in peak strength, yield load, and stiffness (all within approximately 10%) confirm that the developed finite element model provides an accurate and reliable representation of the cyclic behavior of the tested BO-SPSW specimen.

The infill plates of SPSW systems exhibit complex behavior in cyclic loading because of tension fields that form in different orientations; hence, implicit analysis is usually hard to converge. Therefore, the explicit analysis is chosen from the available alternatives for analyzing these continuum finite element models. It is worth mentioning that, as the analysis itself is performed using an explicit solver, some noise is expected in the results [58, 59].

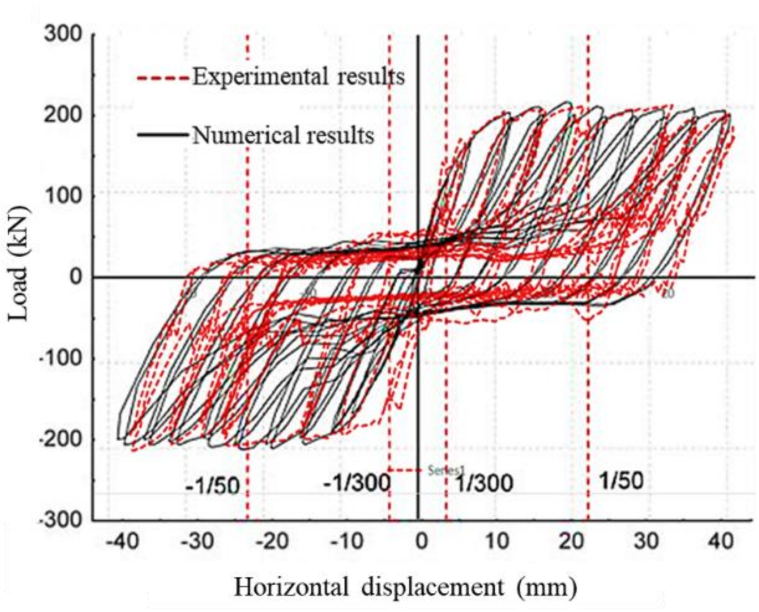


Fig. 3. Comparison of experimental and numerical results.

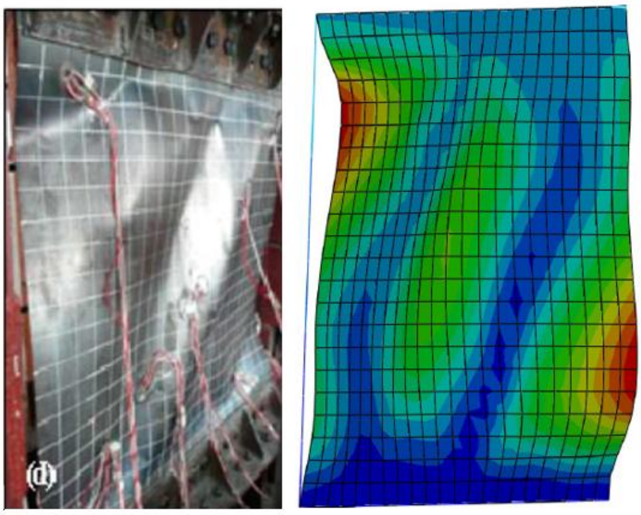


Fig. 4. Comparison of deformations in experimental [33] and numerical model of BO-SPSW specimen.

4. Numerical results and discussions

4.1. Effect of stiffener arrangement on tension field formation

A BO-SPSW subjected to lateral load is analogous to a plate-girder in shear in which the vertical boundary elements, horizontal boundary elements, and the infill plate are similar to flanges, stiffeners, and web of the plate girder, respectively. The ultimate shear strength of plate girders results from the shear buckling strength of the plate girder's web and the tension field formed within it [60]. However, the shear buckling strength is ignored in thin web plates, as they are assumed to buckle right after being subjected to loading [61]. The flanges of plate girders are sufficiently stiff to make it possible for the plate girder's web to form a complete tension field. Hence, as the vertical boundary elements are separated in BO-SPSW, the Partial Tension Field (PTF) is assumed to be similar to the one found in plate girders. Fig. 5 illustrates the PTF in side-stiffened BO-SPSW specimens.

Evidently, it can be seen that the PTF is formed along the web plate height, meaning that the plate still buckles globally. In addition, Fig. 6 indicates that the local tension fields emerge in each subpanel individually in cross-stiffened specimens, and the stiffeners efficiently change the buckling mode of the steel plate from global to local buckling modes in subpanels. Also, according to Fig. 7, the PTF appears between the beams and the adjacent horizontal stiffeners, improving the performance of BO-SPSW. Also, the middle subpanel does not play a considerable role in the PTF formation.

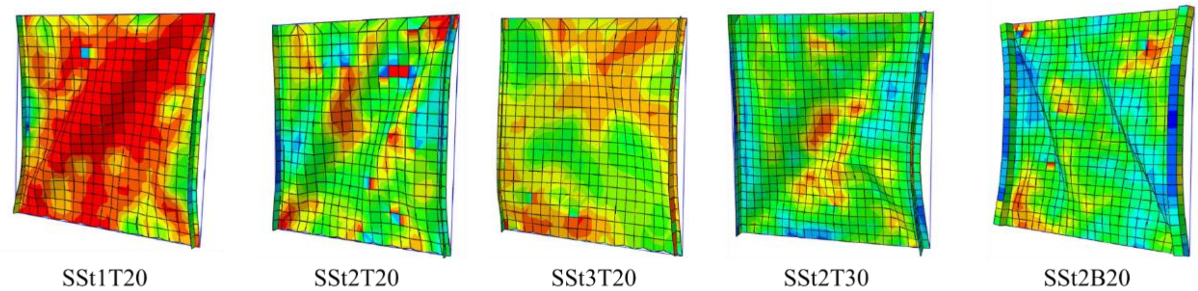


Fig. 5. Partial tension field in side-stiffened specimens.

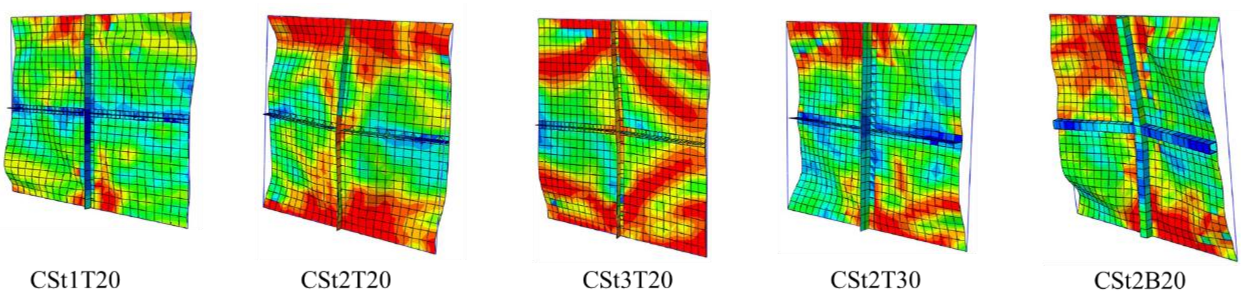


Fig. 6. Partial tension field in cross-stiffened specimens.

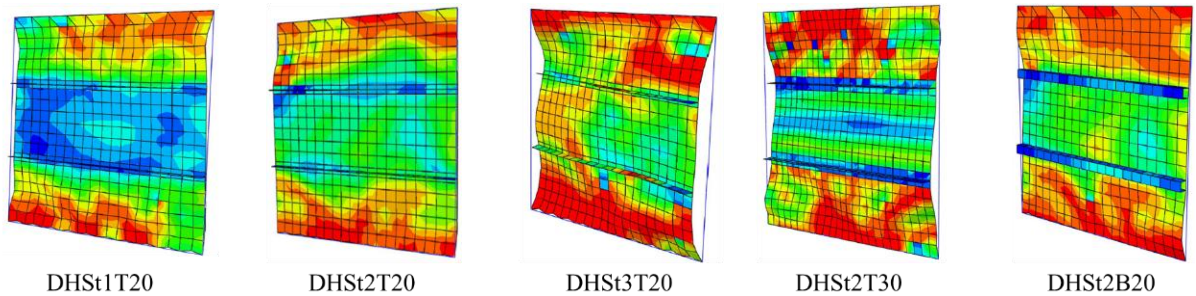
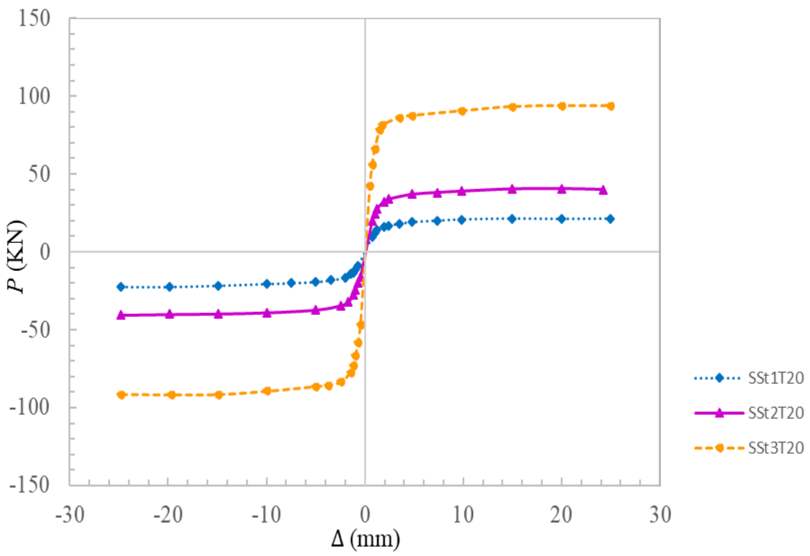


Fig. 7. Partial tension field in double-horizontally stiffened specimens.

4.2. Effect of web plate thickness

In common fully-connected SPSWs, by increasing the thickness of the infill plate, the overall structural performance of the system, such as the ultimate strength, stiffness, and energy absorption capacity, improves. Nevertheless, it may also result in designs that are not economically cost-effective due to the increase in the demand for boundary elements [3]. On the other hand, in BO-SPSWs, there is no contact between the infill plate and the boundary columns, making it possible to increase the thickness of the web plates freely. As evidently illustrated in Fig. 8, the ultimate strength, stiffness, and energy absorption capacity of the stiffened BO-SPSWs are increased in and throughout all arrangements of stiffeners by utilizing a thicker web plate. However, it is noticeable that the ductility ratio (μ) of the system, which is defined as the ratio of the ultimate displacement (Δ_u) to yielding displacement (Δ_y), is independent of plate thickness and is based on the geometry of the specimen rather than the infill plate thickness. Since yielding in SPSW systems develops gradually and does not exhibit a sharply defined transition, the yield point was determined from the equivalent monotonic backbone curve using a bilinear idealization of the response. Moreover, there is no sudden strength degradation in the hysteresis curves of the studied specimens, meaning that this system can be used as a reliable structural system.



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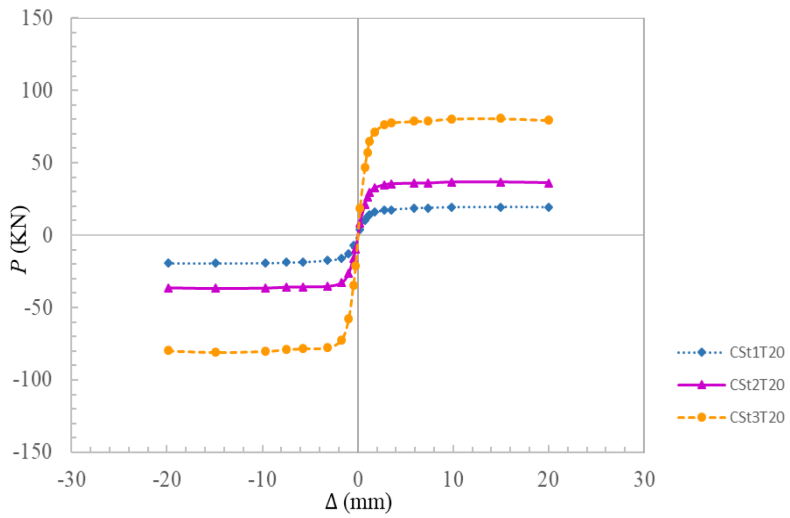

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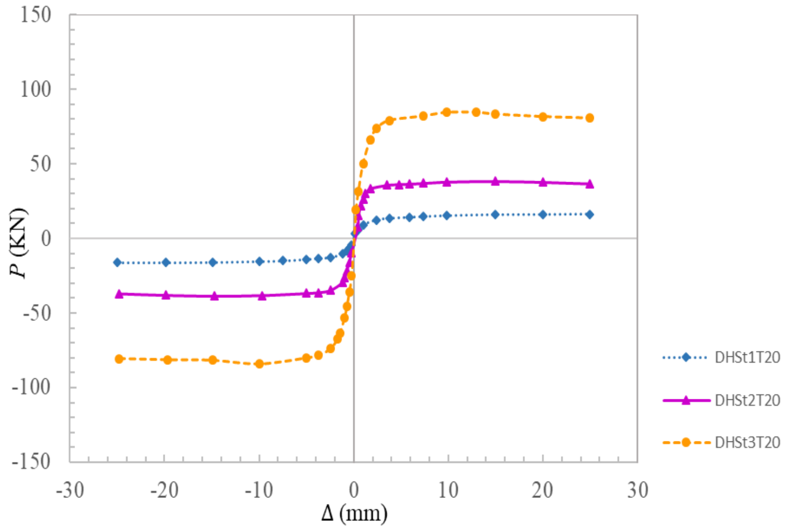
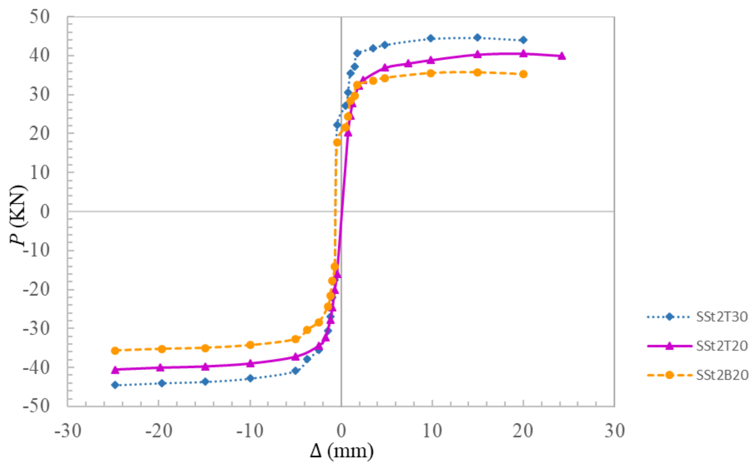


(c)

Fig. 8. Effect of web plate thickness on (a) side-stiffened, (b) cross-stiffened, and (c) double-horizontally stiffened.

4.3. Effect of stiffener section

The tension field in fully-connected SPSWs emerges in the whole infill plate. In contrast, the tension field in BO-SPSWs is partial and appears in different patterns, as discussed in previous sections. In this part, the BO-SPSWs with a consistent plate thickness categorized in three different stiffener arrangements are investigated with attention to the section of stiffeners. As evidently presented in Fig. 9, in all arrangements of stiffeners, using T-shape stiffeners results in higher yielding and ultimate strength compared to box stiffeners, which are more significant in double-horizontally stiffened BO-SPSW specimens (Fig. 9 (c)). Also, increasing the stiffener section from T20x20x2 to T30x30x3 considerably increases the ultimate strength and stiffness of the BO-SPSW systems in all arrangements of stiffeners.



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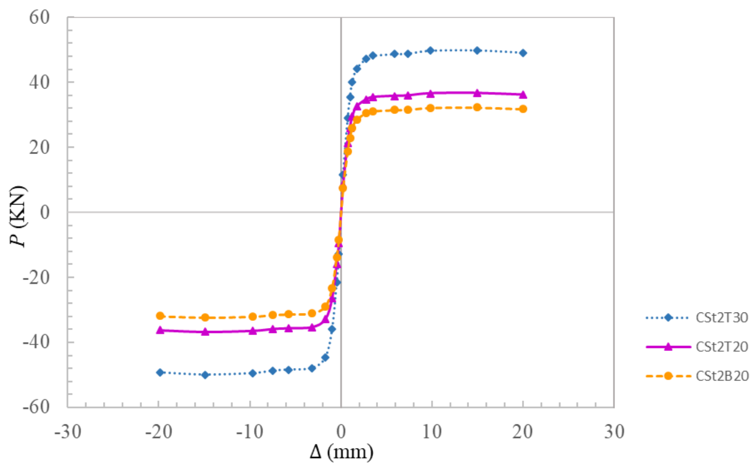

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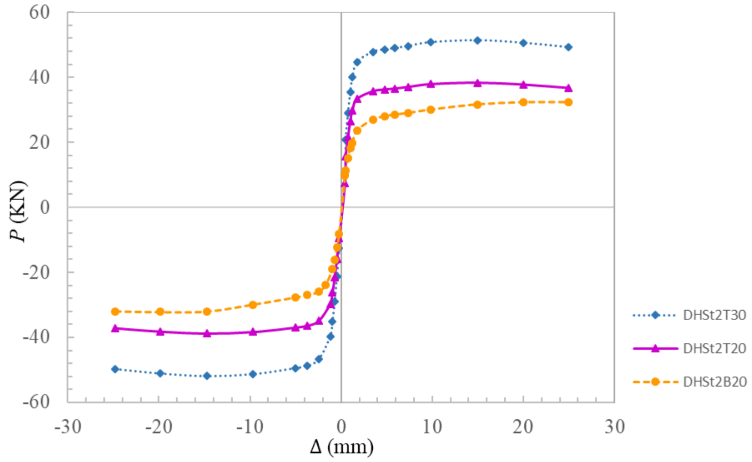
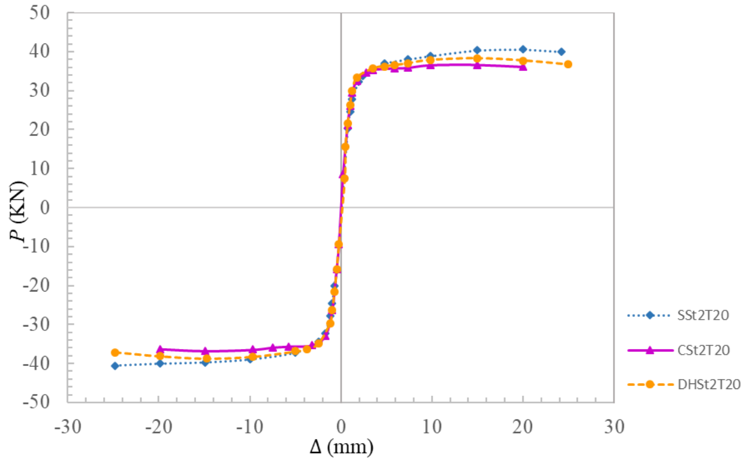


(c)

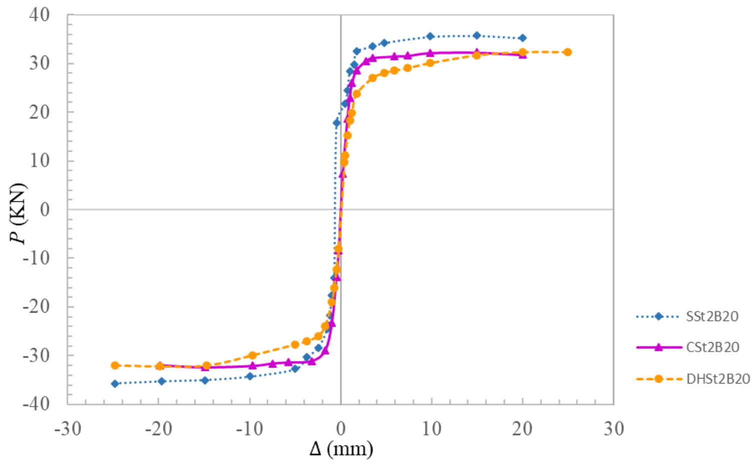
Fig. 9. Effect of stiffener section on (a) side-stiffened, (b) cross-stiffened and (c) double-horizontally stiffened.

4.4. Effect of stiffener arrangement

One of the most critical parameters in the design of stiffened BO-SPSWs is the section and arrangement of the stiffeners. Thus, in order to capture the effect of stiffener arrangement, two types of stiffeners with equal cross sections, namely T20x20x2 and B20x20x1, are selected and shown in Fig. 10 (a) and (b), respectively. Fig. 10 (a) illustrates that the stiffness, yielding strength, and ductility ratio do not change in different stiffener arrangements when using T-shape stiffeners. However, the ultimate strength of the side-stiffened specimen is a bit more than that of the cross-stiffened specimen, which both are higher than that of the double-horizontal specimen. In addition, Fig. 10 (b) shows that the stiffness and yielding strength of the side-stiffened specimen are more than those of the cross-stiffened specimen, which both are more than that of the double-horizontal specimens when utilizing box stiffeners.



(a)



(b)

Fig. 10. Effect of stiffener arrangement using (a) T-shape stiffener and (b) box stiffener.

4.5. Comparison of energy absorption

The energy absorption capacity is determined as the area under the force-displacement curve of each specimen. Fig. 11 (a) compares energy absorption in different infill plate thicknesses with T20x20x2 used as stiffener section in various arrangements of stiffeners. Evidently, it can be seen that by increasing the web plate thickness, the energy absorption capacity of the BO-SPSW system increases significantly. Besides, it is found that the energy absorption capacity of side-stiffened specimens is remarkably more than double that of horizontally and cross-stiffened specimens. Fig. 11 (b) illustrates the comparison of energy absorption capacity in different stiffener sections. As seen in Fig. 11 (b), using T-shape stiffeners provides more energy absorption capacity than box stiffeners with the same cross-sectional area. Moreover, by increasing the dimensions of the stiffeners, the energy absorption capacity increases. Also, the side-stiffened specimens exhibit the best energy absorption performance among all other arrangements of stiffeners.

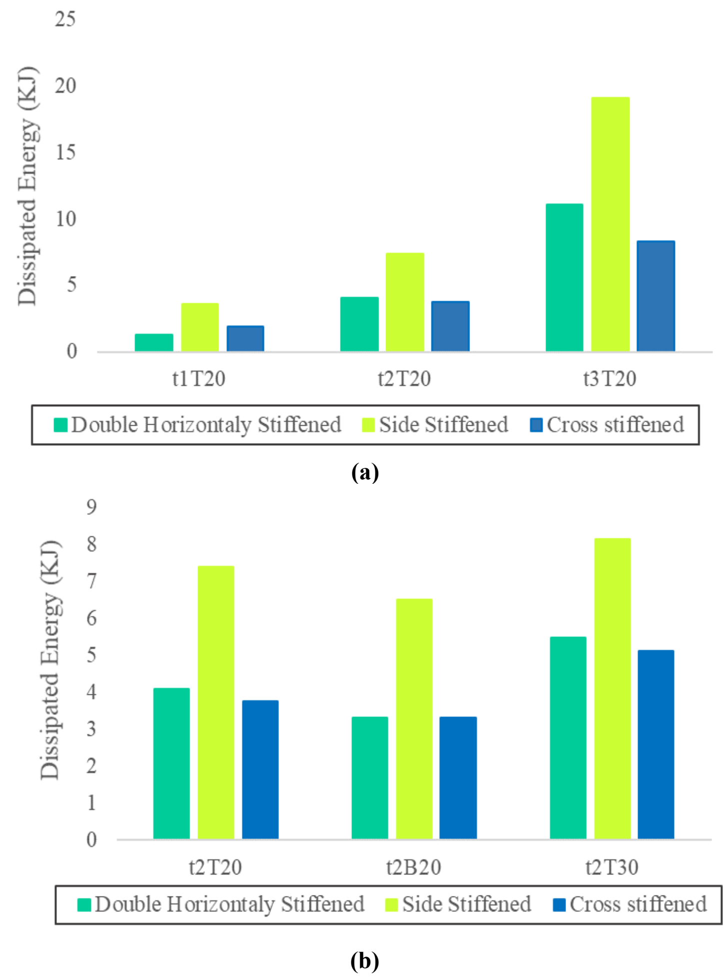


Fig. 11. Comparison of energy absorption capacity in (a) different infill plate thickness and (b) different stiffener sections.

5. Practical implications and future research

From a practical perspective, the numerical results highlight several trends that may assist engineers in the design of stiffened BO-SPSWs. Increasing the web plate thickness was found to significantly enhance the lateral stiffness, ultimate shear capacity, and energy dissipation capability of the system, while also delaying excessive out-of-plane deformations. In addition, the inclusion of stiffeners improved the stability of the hysteretic response by promoting a more uniform stress distribution in the web plate and delaying local buckling effects. Appropriate stiffener arrangements therefore contribute to more stable cyclic behavior and improved structural performance under seismic loading. Although the present study focuses on behavioral trends rather than formal design provisions, the findings suggest that the combined use of adequately thick web plates and properly arranged stiffeners can be an effective strategy for improving the seismic performance of BO-SPSWs. Further studies involving broader parametric ranges and design-oriented calibration are recommended to establish detailed design guidelines.

In addition to structural performance, practical considerations such as fabrication complexity and construction cost are important in selecting an appropriate stiffener arrangement. Side-stiffened configurations generally require fewer stiffening elements and provide easier welding access, which may simplify fabrication and installation. In contrast, cross-stiffened and double-horizontally stiffened configurations involve additional stiffeners and welding operations that may increase fabrication time and cost. Therefore, from a practical standpoint, side-stiffened arrangements may offer advantages in terms of constructability while still providing favorable structural performance.

The findings of this study provide insight into the cyclic behavior and performance trends of stiffened beam-only connected steel plate shear walls with different stiffener configurations. Although the present investigation is based on detailed finite element simulations at the component level, further research may expand upon these results through additional parametric studies considering a wider range of geometric properties, material characteristics, and stiffener layouts. Experimental investigations would also be valuable to further validate the numerical observations and to better capture potential local effects that may arise in practical applications. Moreover, future studies may evaluate the seismic performance of BO-SPSW systems within complete structural frames subjected to earthquake ground motions in order to assess their global response characteristics. Such investigations could also contribute to the estimation of seismic performance factors, including the response modification factor (R-factor), thereby facilitating the development of design-oriented recommendations for the practical implementation of stiffened BO-SPSW systems in seismic-resistant structures.

6. Conclusion

This study investigates the structural performance of stiffened beam-only connected steel plate shear walls (BO-SPSWs) using detailed finite element analysis. BO-SPSW systems provide a more economical alternative to conventional SPSWs because the infill plate is detached from the vertical boundary elements, reducing the demand on columns. The parameters considered in this study include the web plate thickness, the dimensions and cross-sections of stiffeners, and the arrangement of stiffeners. Based on the numerical results, the following conclusions can be drawn:

- The stiffened BO-SPSW system exhibits stable cyclic behavior under repeated loading, with no significant or sudden strength degradation observed in the hysteretic response.
- In BO-SPSWs with side, cross, and double-horizontal stiffeners, partial tension fields develop within the infill plate. These tension fields form in the subpanels created by the stiffeners and between the stiffeners and the adjacent beams.
- T-shaped stiffeners provide higher ultimate strength compared with box stiffeners having the same cross-sectional area. In addition, increasing the stiffener dimensions leads to an increase in the ultimate strength for all stiffener arrangements.
- Increasing the web plate thickness or the stiffener dimensions significantly enhances the energy absorption capacity of the system. Among the investigated configurations, side-stiffened specimens demonstrate the highest energy dissipation capacity.
- The ultimate strength of BO-SPSWs is influenced by the stiffener arrangement. Side-stiffened configurations generally exhibit higher strength compared with cross-stiffened and double-horizontal stiffened systems, while the overall stiffness and ductility remain relatively similar when T-shaped stiffeners are used.
- Increasing the number of stiffeners in the web plate improves resistance to local buckling, resulting in a more uniform tension field distribution and enhanced overall stability of the BO-SPSW system.
- The performance of BO-SPSWs shows relatively low sensitivity to boundary frame stiffness, indicating that the system can maintain reliable strength and ductility even when simple or semi-rigid beam-to-column connections are used.

Statements & Declarations

Author contributions

Zeinab Meghdadi: Conceptualization, Methodology, Validation, Formal analysis, Writing – Original Draft, Writing-Review & Editing.

Mohammad Shabanlou: Conceptualization, Methodology, Validation, Writing-Review & Editing.

Massood Mofid: Conceptualization, Supervision, Methodology, Validation, Writing-Review & Editing.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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