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An Experimental Study of a Novel Type of Steel Plate Shear Wall with Diagonal Tension Field Guiding Stiffeners

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Abstract – This paper proposes a new kind of steel plate shear wall that can withstand lateral forces. The shear wall's corners were reinforced with inclined stiffeners that served as tension field guiding stiffeners, and a middle link beam was constructed like an eccentrically braced frame (EBF). After the diagonal members were added to the shear wall, the system looked like an EBF system combined with a steel plate shear wall system. A scaled specimen of the shear wall with guiding stiffeners was constructed and subjected to cyclic loading to examine the cyclic performance of the system. In the suggested system, the guiding stiffeners can change the form of the tension field of the web plate, leading plastic stresses away from the column face toward the link beam. This helps to keep the columns and connections safe. As a result, two-stage ductile fuses are contained in the failure mechanism of the proposed system. The first fuse is the yielding of the web plate in tension, and the second fuse includes flexural or shear plastic hinges of the link beam ends. The placement of the plastic hinges could be specified by altering the orientation of the diagonal stiffeners.

Keywords**:** Steel plate shear wall, Stiffener, Cyclic test, Finite element analysis, Hysteretic behaviour

1. Introduction

The good shear strength, energy absorption, stiffness, and ductility of steel plate shear walls (SPSWs) have made them a popular choice for withstanding lateral forces [1], [2]. SPSWs have been successfully used to renovate and retrofit existing structures as well as to build new structures. According to AISC 341-16, moment-resisting connections are used for the connections of the shear walls in high seismicity regions [3]. However, the connections and column experience brittle failure and increasing deformation as a result of this kind of connection. Columns in shear walls should remain safe because of their significant role in supporting vertical loads. As a result, the researchers are working to move the failure region of steel shear walls and moment frames to expected ductile portions of the beam away from connections and columns [2], [4]. Some researchers have stiffened the shear walls with different stiffeners for this purpose. The addition of stiffeners might efficiently spread the tension field, restrict out-of-plane buckling of the plate, and significantly reduce the moment acting on the column. Furthermore, stiffeners might alter the failure region, causing the structure to display ductile behaviour. Transverse braces, according to Yu et al. [5], improve the shear capacity, ductility, and energy absorption of the walls. Also, it could uniformly distribute stress and restrict the out of plane deformations in the web, leading to an extensive reduction of bending moments acting on the column. In addition, some stiffeners dividing the plate into smaller segments may reduce the plate's height-to-thickness ratio, delaying buckling, and increasing load-carrying capacity and stiffness [6]. Meng et al. [7] enhanced the ability to withstand collapse by stiffening the wall with stiffened triangular steel plates (SF-SPSW). Cao et al. [8] investigated unstiffened and stiffened shear walls using external X-shaped stiffeners. They concluded that the X-shaped stiffeners could enhance the seismic performance of the system. Under combined loads, Xu et al. [9] researched the buckling performance of steel shear walls using stiffeners (S-SPWs). Some initial stiffness formulas for bars and stiffeners have been proposed. Comparison of these relationships with finite element analyses revealed a good accuracy. Yu et al. [10] investigated both numerically and experimentally the behaviour of steel walls using multi-rib restrainers. According to the findings, using these stiffeners reduces the maximum story displacement and out-of-plane deformation. Daya Karthic et al. [11] investigated stiffened plates with different configurations of stiffeners. Wu et al. [12], [13] investigated diagonally stiffened stainless steel shear walls experimentally and numerically. A comparison between the stainless and other steel walls was carried out. Furthermore, a method for designing is provided. Ma et al. [14] suggested and tested a scaled model of a novel buckling-stiffened steel plate shear wall (BR-LYP-SPSW). They showed that increased peak ground acceleration would result in a reduced dynamic amplification factor of acceleration and frequency and an increased damping ratio. Wang et al. [15]

proposed a new resisting system that consists of a low-yield point plate stiffened by diagonal T-shaped stiffeners. The system is introduced to improve the shear wall's stability and seismic behavior. Haddad et al. [16] compared experimentally unstiffened shear walls with different configurations of stiffened shear walls. Some studies were performed on the damage and fracture of structural systems[17]–[19]. Alavi and Nateghi [20] combined diagonal stiffeners with a central perforation to create a novel type of shear wall. As another solution for limiting out-of-plane buckling of the plate, it has been proposed to use corrugated steel plates, as investigated through experimental and numerical studies [33]. Moreover, a number of studies have been done on shear walls with various configurations of openings to pass service utilities. Openings could reduce the stiffness and strength of the wall. To compensate for the degradation, it is possible to combine the openings with some stiffeners [25] [26]. Valizadeh et al. [27] introduced a new lateral load-resisting system with butterfly-shaped links and investigated its seismic behavior numerically and experimentally. According to the findings, the butterfly-shaped link wall reduces stability while significantly increasing energy absorption.

In the current study, a test specimen was produced and stiffened with tension field guiding stiffeners. A thin plate, boundary members, diagonal tension field guiding stiffeners, and some plates inserted in the boundary members at the points of the guiding stiffener connection to these members make up the proposed shear wall. Eight channel sections serve as tension field-guiding stiffeners in each shear wall. After that, cyclic loading was applied to the test specimen. The diagonal tension field guiding stiffeners were proposed as an alternative to traditional stiffeners for lowering the tensile force acting on columns and connections. (see Fig. 1). The suggested tension field guiding stiffeners are predicted to modify the tension field pattern of the web plate, increasing the cyclic performance of the shear wall. The shear walls, as expected, could improve the proposed system's maximum shear capacity. Notably, by inserting diagonal elements to the shear wall, the system resembled a mix of a steel shear wall system and an eccentrically braced system, which had not been done previously. The diagonal stiffeners can restrict the out-of-plane deformation of the web plate. The diagonal members, on the other hand, could drive the plastic hinges toward the link beam away from the column. This could protect the columns and keep them in the elastic zone even in large drifts.

2. Proposed model

The general arrangement of the tested model is depicted in Fig. 1. The suggested system was designed to achieve the following goals:

a) Two-phase ductile fuses: In the system, two ductile fuses could form: The first fuse is the yielding of the web plate in tension, and the second fuse includes flexural or shear plastic hinges of the link beam ends. Fig. 2 displays the suggested system's yield procedures when subjected to lateral loading.

b) Enhancing shear resistance: The diagonal stiffeners operate as a bracing system that improves the overall shear capacity of the shear wall.

c) Variable hinge position: The placement of the plastic hinges could be specified by altering the orientation of the diagonal stiffeners.

d) Changing the tension field pattern: The suggested technology, as shown in Fig. 2, is intended to alter the tension field pattern of the infill plate. T1, which leads toward the intersection of the diagonal stiffeners and beams, is projected to be the most prominent tension field. The parallel tension fields to field T2 would likewise arise, but the magnitude would be lowered at the corners (illustrated with dotted lines). The demand at the beam-column connection will be reduced as a result.

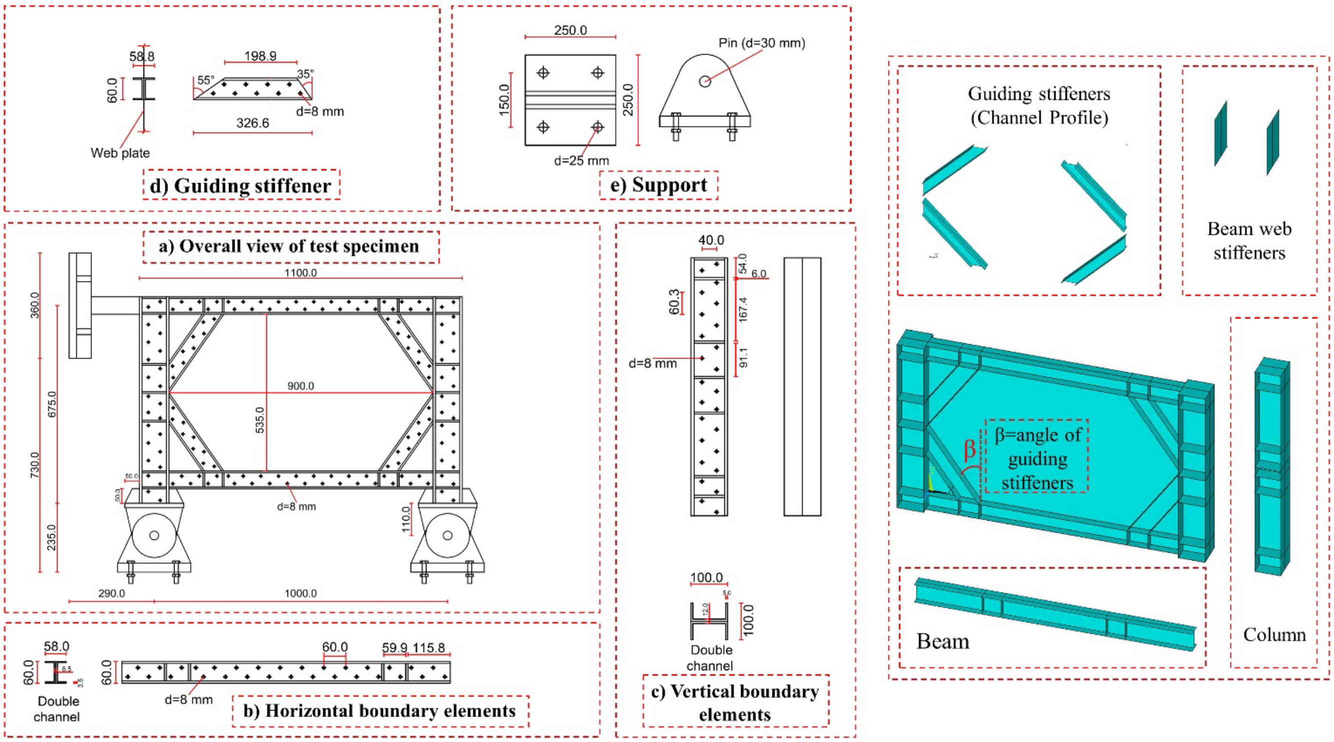

Fig. 1: the test specimen's overall dimensions and arrangement.

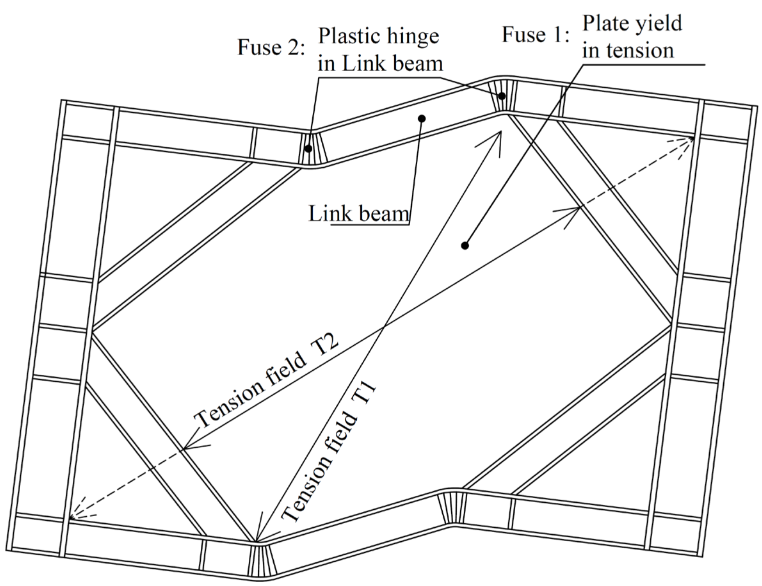

Fig. 2: The suggested system's lateral load mechanism.

3. Test setup

Cycle loading tests were performed on a 1:6 scale specimen to evaluate the performance of the suggested steel shear wall with tension field guiding stiffeners. This test specimen is comparable to the tests that Sahebjam and Showkati [28] and

Vian et al. [29] have conducted, but it is designed without a perforation. The base connections are hinged due to the limits of the laboratory setup and to avoid the moment transferred to the laboratory's strong floor. The connections of the boundary elements are ordinary fully rigid connections. This experiment was conducted in Iran at the structure laboratory of Tabriz University. Table 1 and Fig. 3 provide further specifics about the test sample's dimensions and arrangement.

Table 1: The specifics of the test sample:
(a) The plate's specifics.

Plate thickness (t, mm)	Width (the distance between the centerlines of the columns) (L, mm)	Height (the distance between the centerlines of the beams) (h, mm)
0.8	1000	595

(b) Specifications for boundary members and guiding stiffeners.

member	Flange width (mm)	Flange thickness (mm)	Web Height (mm)	Web thickness (mm)
Column (Double channel)	100	5	100	12
Beam (Double channel)	58	3.5	60	8.5
Guiding stiffener (channel)	29	3.5	60	4.25

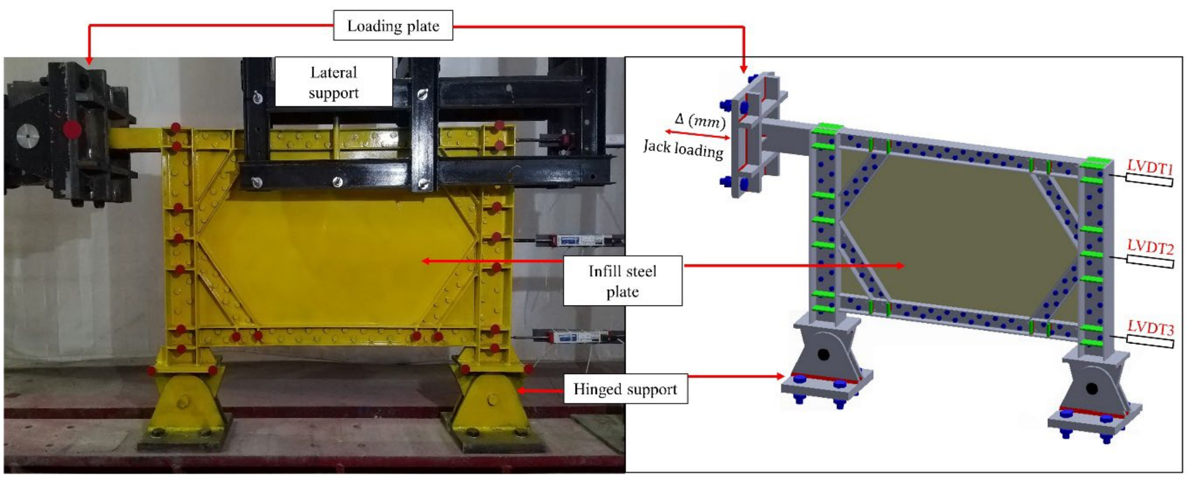

Fig. 3: The view of the specimen.

The design strategy is based on the unstiffened steel shear wall design found in Steel Design Guide 20 and AISC 341-16 [3], [30]. The test specimen's web plate and boundary members, not guiding stiffeners, were designed using this design method.

The stiffeners are attached to the web plate using bolts (according to Fig. 1). The major function of these stiffeners is to interact with the boundary components and affect the general frame's deformation pattern. The diagonal guiding stiffener angle (β) is intended to be 35 degrees. According to the ASTM [31] and tensile coupon test outcomes, the mean yield and ultimate stresses of the members are F_y=243 MPa and F_u=381 MPa for the beams, guiding stiffeners, and columns, respectively, and F_y=148 MPa and F_u=279 MPa for the infill plate. Young's modulus and Poisson's ratio for the plate are 200 GPa and 0.3, respectively. Lateral bracings were employed at three spots on the top beam to prevent out-of-plane distortion.

3.1. Loading procedure

The specimen was subjected to lateral loading using a servo-hydraulic jack that could support a maximum of 50 tons. tons. The loading was displacement-controlled and quasi-static and was applied along the top beam’s centreline, according according to Fig. 3. There are uncertainties in the yield deformation value calculation in the ATC-24 loading procedure [32]. [32]. As a result, the SAC loading method of the AISC seismic standard [3] was altered and applied. The SAC loading procedure and the modifications are shown in Table 2 and Fig. 4.

Table 2: The protocol of loading.

SAC protocol		**Applied protocol**	
(rad)θ	Cycles	(rad)θ	Cycles
-	-	0.0025	3
0.00375	6	0.00375	3
0.005	6	0.005	3
0.0075	6	0.0075	3
0.01	4	0.01	3
0.015	2	0.015	2
0.02	2	0.02	2
0.03	2	0.03	2
0.04	2	0.04	2
0.05	2	0.05	2
0.06	2	0.06	2
0.07	2	0.07	2
0.08	2	0.08	2

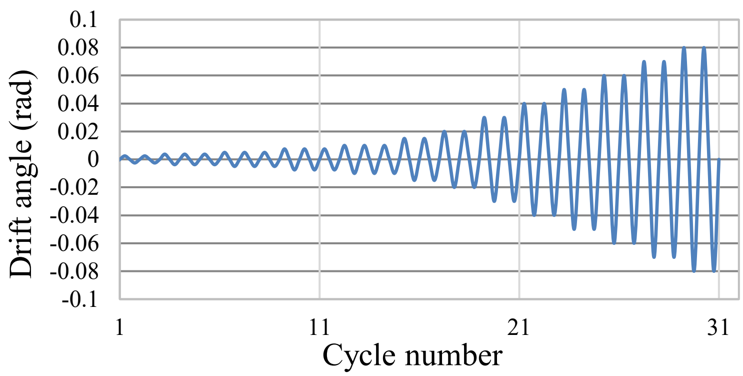

Fig. 4: The applied loading.

4. The findings and conclusions

A novel shear wall with diagonal tension field guiding stiffeners is introduced in this study. A laboratory test specimen was created, and a test was conducted on the suggested model. The test results were utilized to analyze the specimen's behaviour during each cycle. The hysteresis curve of base shear to the displacement of the top beam is shown in Fig. 5. The plate began to yield at an approximate lateral force of 45 kN and revealed inelastic behaviour on the hysteresis envelope curve. As the force continued, the tension field of the web plate developed, and buckling waves emerged. By raising the load, another yield point in the force-drift curve was generated. The beginning of the flexural plastic hinge at the beam is associated with this yield point. But since the vertical boundary elements and connections had not failed yet, loading could proceed. Thus, the utilization of the beam's entire capacity is one of the proposed system's benefits. The specimen loading could not be continued beyond 4% drift due to laboratory equipment limitations (displacement of 31.4mm). The specimen's cyclic hysteresis curve is stable, as can be observed. During loading, the columns of the test specimen remained intact without yielding. On the other hand, the beams of the test specimen yielded where they were connected to the guiding stiffeners.

The specimen at 4% drift is shown in Fig. 6. It is evident that there was local buckling of the beam flange near the where the beams were attached to the guiding stiffeners. It should be mentioned that the section is not compact due to beam flanges' width-to-thickness ratio of roughly 16. However, the system could reach 4 percent drift without lowering the shear strength. Additionally, the plate has a buckling wave angle of about 45° with respect to the vertical direction.

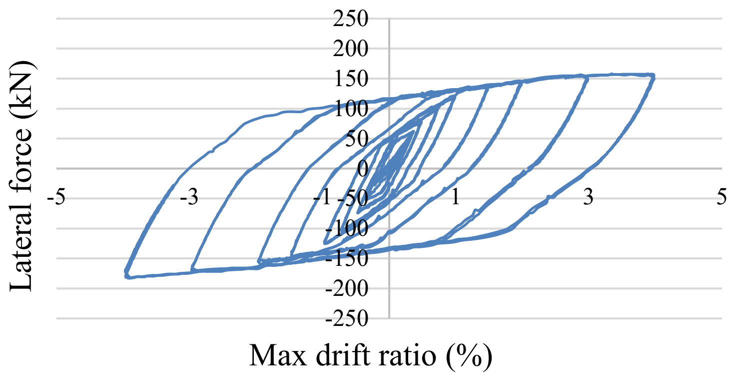

Fig. 5: The test specimen's hysteresis curves show up to 4% drift.

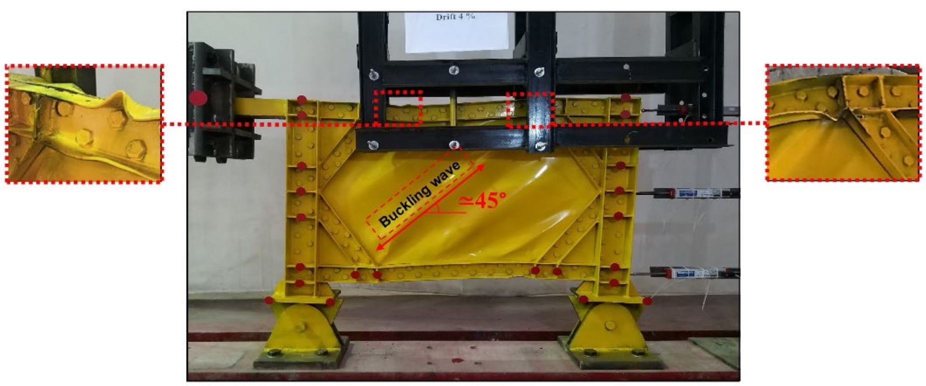

Fig. 6: The test specimen's deformation and failure at 4% drift.

In addition, the suggested system includes two-stage ductile fuses. Under the influence of the tension field, the plate would begin to yield, serving as the first fuse. After that, the yielding at the ends of the link beam would happen by increasing the loading. These areas are the second fuse. The fuses increase energy dissipation in the proposed system. The angle of the suggested stiffeners could be employed to alter the development area of the plastic strain in the web plate.

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References

[1] J. W. Berman, O. C. Celik, and M. Bruneau, “Comparing Hysteretic Behavior of Light-Gauge Steel Plate Shear Walls and Braced Frames,” *Eng. Struct.*, vol. 27, no. 3, pp. 475–485, Feb. 2005, doi: 10.1016/J.ENGSTRUCT.2004.11.007.

[2] J. Berman and M. Bruneau, “Experimental Investigation of Light-Gauge Steel Plate Shear Walls,” *J. Struct. Eng.*, vol. 131, no. 2, pp. 259–267, 2005, doi: 10.1061/(ASCE)0733-9445(2005)131:2(259).

[3] *ANSI/AISC 341-16: Seismic Provisions for Structural Steel Buildings*. Chicago, Illinois, USA, 2016.

[4] J. Yan, Y. Chen, and X. Lin, “Finite Element Analysis and Parametric Studies on Hysteretic Behaviours of High Strength Steel T-Joints with Damage-Control Fuses,” *Thin-walled Struct.*, vol. 148, no. 106574, 2020.

[5] J. Yu, X. Feng, B. Li, and J. Hao, “Cyclic Performance of Cross Restrained Steel Plate Shear Walls with Transverse Braces,” *Thin-Walled Struct. J.*, vol. 132, pp. 250–264, 2018, doi: 10.1016/j.tws.2018.08.020.

[6] G. U. O. Yan-lin, C. H. E. N. Guo-dong, and M. I. A. O. You-wu, “Elastic Buckling Behavior of Steel Plate Shear Wall with Cross or Diagonal Stiffeners,” *Eng. Mech.*, vol. 23, no. 2, pp. 84–91, 2006, Accessed: Dec. 11, 2021. [Online]. Available: https://en.cnki.com.cn/Article_en/CJFDTotal-GCLX200602014.htm.

[7] B. Meng, J. Hao, and W. Zhong, “Numerical Study on the Anti-Progressive Collapse Performance of Steel Frame-Steel Plate Shear Wall Structures,” *J. Build. Eng.*, vol. 35, p. 102049, 2021, doi: 10.1016/j.jobe.2020.102049.

[8] Z. Cao, Z. Wang, P. Du, H. Liu, and F. Fan, “Quasi-static experiments on steel plate shear walls reinforced with X-shaped restrainers,” *J. Build. Eng.*, vol. 31, p. 101451, 2020, doi: 10.1016/j.jobe.2020.101451.

[9] Z. Xu, G. Tong, and L. Zhang, “Design of vertically stiffened steel plate walls under combined uniaxial compression and shear loads,” *Structures*, vol. 26, pp. 348–361, 2020, doi: 10.1016/j.istruc.2020.04.024.

[10] J. G. Yu, X. T. Feng, B. Li, and Y. T. Chen, “Effects of non-welded multi-rib stiffeners on the performance of steel plate shear walls,” *J. Constr. Steel Res.*, vol. 144, pp. 1–12, 2018, doi: 10.1016/j.jcsr.2018.01.009.

[11] R. D. Karthic, R. Risheek, N. Harish, K. J. Geonel, and L. B. Rao, “Buckling analysis of structural steel panel with multiple configuration of stiffeners,” *Mater. Today Proc.*, vol. 76, 2023.

[12] Y. Wu, S. Fan, H. Zhou, Y. Guo, and Q. Wu, “Cyclic behaviour of diagonally stiffened stainless steel plate shear walls with two-side connections: Experiment, simulation and design,” *Eng. Struct.*, vol. 268, p. 114756, 2022.

[13] Y. Wu, S. Fan, Y. Guo, S. Duan, and Q. Wu, “Experimental study and numerical simulation on the seismic behavior of diagonally stiffened stainless steel plate shear walls under low cyclic loading,” *Thin-Walled Struct.*, vol. 182, p. 110165, 2023.

[14] Z. yong Ma, J. ping Hao, and H. sheng Yu, “Shaking-table test of a novel buckling-restrained multi-stiffened low-yield-point steel plate shear wall,” *J. Constr. Steel Res.*, vol. 145, pp. 128–136, 2018, doi: 10.1016/j.jcsr.2018.02.009.

[15] M. Wang, X. Zhang, L. Yang, and W. Yang, “Cyclic performance for low-yield point steel plate shear walls with diagonal T-shaped-stiffener,” *J. Constr. Steel Res.*, vol. 171, p. 106163, 2020, doi: 10.1016/j.jcsr.2020.106163.

[16] O. Haddad, N. H. Ramli Sulong, and Z. Ibrahim, “Cyclic performance of stiffened steel plate shear walls with various configurations of stiffeners,” *J. Vibroengineering*, vol. 20, no. 1, pp. 459–476, 2018, doi: 10.21595/jve.2017.18472.

[17] L. Esteva, “Optimum damage- control policies for structural systems under seismic risk conditions,” *Proc., 3rd World Conf. Struct. Control. F. Casciati, ed., Wiley, Chichester, U.K.*, pp. 33–46, 2002.

[18] A. Es’haghi Oskui, E. Haddadi, and M. Ebrahimi, “A technical approach toward pre-crack generation and

its effect on the fracture behavior of polymeric materials," *Eng. Fract. Mech.*, vol. 274, p. 108780, 2022.
[19] S. Hashemian, P. M. Keshtiban, and A. E. haghi Oskui, "Fracture behavior of the forged aluminum 7075-T6 alloy under mixed-mode loading conditions," *Eng. Fail. Anal.*, vol. 140, p. 106610, 2022.
[20] E. Alavi and F. Nateghi, "Experimental study on diagonally stiffened steel plate shear walls with central perforation," *J. Constr. Steel Res.*, vol. 89, no. 1992, pp. 9–20, 2013, doi: 10.1016/j.jcsr.2013.06.005.
[21] J.-Q. Zuo, B.-L. Zhu, Y.-L. Guo, C.-B. Wen, and J.-Z. Tong, "Experimental and Numerical Study of Steel Corrugated-Plate Coupling Beam Connecting Shear Walls," *J. Build. Eng.*, vol. 54, p. 104662, 2022.
[22] J. Z. Tong, Y. L. Guo, and W. H. Pan, "Ultimate shear resistance and post-ultimate behavior of double-corrugated-plate shear walls," *Journal of Constructional Steel Research*, vol. 165. 2020, doi: 10.1016/j.jcsr.2019.105895.
[23] S. Shon, M. Yoo, and S. Lee, "An experimental study on the shear hysteresis and energy dissipation of the steel frame with a trapezoidal-corrugated steel plate," *Materials (Basel).*, vol. 10, no. 3, 2017, doi: 10.3390/ma10030261.
[24] H. Jin *et al.*, "Simplified inelastic global buckling theory of non-buckling corrugated steel shear walls for seismic energy dissipation," *Thin-Walled Struct.*, p. 107209, 2020, doi: 10.1016/j.tws.2020.107209.
[25] A. Farzampour and J. A. Laman, "Behavior prediction of corrugated steel plate shear walls with openings," *J. Constr. Steel Res.*, vol. 114, pp. 258–268, 2015, doi: 10.1016/j.jcsr.2015.07.018.
[26] N. Paslar, A. Farzampour, and F. Hatami, "Investigation of the infill plate boundary condition effects on the overall performance of the steel plate shear walls with circular openings," *Structures*, vol. 27, pp. 824–836, 2020, doi: 10.1016/j.istruc.2020.06.031.
[27] H. Valizadeh, H. Veladi, B. Farahmand Azar, and M. R. Sheidaii, "The cyclic behavior of Butterfly-shaped Link Steel Plate Shear Walls with and without Buckling-restrainers," *Structures*, vol. 27, no. June, pp. 607–625, 2020, doi: 10.1016/j.istruc.2020.06.012.
[28] A. Sahebjam and H. Showkati, "Experimental study on the cyclic behavior of perforated CFRP strengthened steel shear walls," *Arch. Civ. Mech. Eng.*, vol. 16, no. 3, pp. 365–379, 2016, doi: 10.1016/j.acme.2016.01.009.
[29] D. Vian, M. Bruneau, K. C. Tsai, and Y.-C. Lin, "Special Perforated Steel Plate Shear Walls with Reduced Beam Section Anchor Beams. I: Experimental Investigation," *J. Struct. Eng.*, vol. 135, no. 3, pp. 211–220, Mar. 2009, doi: 10.1061/(ASCE)0733-9445(2009)135:3(211).
[30] R. Sabelli and M. Bruneau, *Design Guide 20 - Steel Plate Shear Walls*. Chicago: American Institute for Steel Construction, INC, Chicago, 2007.
[31] "American Society for Testing and Materials. Committee A-01 on Steel, Stainless Steel and Related Alloys. Standard test methods and definitions for mechanical testing of steel products. ASTM International," 2017.
[32] "Guidelines for Seismic Testing of Components of Steel structures," Report of ATC-24, 1992.