Numerical Methods in Civil Engineering

Journal Homepage: https://nmce.kntu.ac.ir/

Investigation the Effect of Strengthening Various Subpanels in the SPSPs with Two Rectangular Openings

Saeid Sabouri-Ghomi [*] **and Elnaz Ahouri** [**]

Abstract:

In the present research, behavior of SPSPs with two rectangular openings and effect of strengthening different subpanels with various stiffener arrangements is investigated. In the next step, to investigate the effect of changing opening width on the trend of degradation shear stiffness and strength of the panel, the opening width is changed. In the third step, to study the effect of changing opening height on the behavior of the whole panel, the opening height is changed. Based on the results obtained, it is observed that for SPSPs with constant plate thickness and opening dimensions, strengthening various subpanels with different stiffener arrangements has no effect on the values of shear stiffness of the panel, and only the shear strength of the panel is changed. In the case of panels with constant opening dimensions and plate thickness and stiffened corner panels (height of subpanels equal to opening height), changing the number of horizontal and vertical stiffeners to stiff corner panels with different stiffener arrangements, has no effect on shear stiffness. Only the shear strength is changed in these models. For SPSPs with constant opening dimensions and constant plate thickness and different stiffener arrangements to stiff corner panels, by increasing number of both horizontal and vertical stiffeners, no changes on the shear stiffness is created, and its effect on the value of shear strength is negligible. However, using L3T3 and L1T0 stiffener arrangements result in obtaining maximum and minimum values of shear strength, respectively. In addition, the effect of changing opening width in the SPSPs with constant opening height and also the effect of changing opening height in the SPSPs with constant opening width on the values of shear strength and stiffness of the specimens is investigated.

1. Introduction

Nowadays lateral load bearing system steel plate shear wall has extensive applications for constructing new buildings and strengthening existing buildings. According to design guidelines bout SPSP system, stiffened plates in SPSPs are used to prevent global buckling mode of the plate. In addition, using unstiffened SPSPs is also extended prevalently. Results of extensive experimental, analytical and numerical studies on this system approve high initial shear stiffness and shear strength, considerable energy absorption capacity and stable hysteretic characteristics. In this system, because of continuity of steel plate, it is possible to create opening(s) with various numbers, shapes and sizes in the steel plate.

Corresponding author: Professor, Faculty of Civil Engineering, K. N. Toosi University of Technology, Tehran, Iran. E-mail: sabouri@kntu.ac.ir
** Ph.D. Candidate, Faculty of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran.

According to the results obtained from previous studies, existence of opening in steel plate creates considerable stress concentration in opening corners. Additionally, in these panels, considerable in-plane and out-of-plane deformations are created in opening edges and opening corners at large displacements respectively. Some of the most important studies on perforated SPSPs were the studies of Sabouri and Roberts [1-4], on SPSPs with central circular perforation. Sabouri and Sajadi [5,6], investigated the behavior of stiffened SPSPs with single rectangular opening with various ratios to study the effect of changing dimensions of opening on behavioral characteristics of stiffened SPSPs. Sabouri-Ghomi and Mamazizi [7] studied three stiffened steel plate shear panels with two rectangular openings with same dimensions by experimental studies. Distance between openings in the direction of the panel's width was changed, and the effect of changing this parameter was studied. Other objectives of this research were to compare shear stiffness and strength and energy absorption capability of specimens,

to investigate the behavior of different subpanels and deformations of stiffeners. Vian et al. [8], also investigated special perforated SPSPs with reduced beam section anchor beams through numerical and experimental studies. Different perforation patterns were considered in the FE models. They also studied the influence of localized distribution of panel stress and strain between perforations. Based on the numerical and experimental results obtained, design recommendations were proposed. Purba and Bruneau [9], studied seismic performance of unstiffened thin SPSPs with regular pattern of openings by numerical studies. Finite element monotonic pushover analyses were used to analyze the perforated specimens with variation in perforation diameter with three types of boundary conditions: flexible beam laterally braced, rigid floor, and rigid beam. They also proposed design recommendations to design these panels. According to the results of this research, it was shown that the shear strength of SPSPs with a matrix form of regularly spaced circular perforations can be determined as a function of the shear strength of similar un-perforated panel, perforation diameter, and distance between perforations. Chan et al. [10], conducted studies on the stiffness and strength of perforated steel plate shear walls through nonlinear finite element technique. They proposed a linear reduction function to calculate shear stiffness and strength of SPSPs with opening. Ding et al. [11], investigated performance of the corrugated SPSP specimens with openings in modularized-constructions through experimental studies under cyclic loading. Five full-scale quasi-static tests on the CSPSW specimens with and without opening were performed and several design recommendations to effective design of these specimens were proposed according to the experimental results. The results obtained showed that the ultimate strength and energy dissipation ratio are 14.4% and 28.7% higher than the values of these parameters for similar un-perforated CSPSW, respectively. Bhowmick et al. [12], investigated seismic performance of perforated SPSPs. A single story SPSP with two different aspect ratios and eight perforation patterns was studied to investigate suggested shear strength model by numerical FE studies. Results obtained showed that the suggested model is capable of calculating the boundary columns of three sample four-story perforated shear walls, accurately. Mu and Yang [13], conducted numerical and experimental studies on the performance of perforated SPSPs with oblique stiffeners. Moghimi and Driver [14], investigated the column demands in SPSPs with regular perforations using performance-based design procedures. Results of numerical FE studies showed that the net demand on the columns increases in some cases by creating perforations. In addition, structural performance of these perforated specimens is also sensitive to the selection of pattern of holes. Furthermore, beam-to-column connection's flexibility affects the column demands considerably. Choi and Park [15], conducted experimental studies to investigate the structural performance of SPSP specimens with various infill plate designs. Five three-story steel plate shear walls with thin infill plates were considered in this research. The effect of changing type of plate to frame element connections (welded connection versus bolted connection), length of the welded connection (full

connection versus partial connection), and opening in the steel plate were considered in this research. According to the numerical and experimental results obtained, design recommendations were proposed. Shekastehband et al. [16], studied hysteretic behavior of SPSP specimens with beam-only connected infill plates. Bahrebar et al. [17], investigated the nonlinear buckling analysis of SPSPs with trapezoidally corrugated and perforated infill plates through numerical studies. Variation of shear stiffness, shear strength, ductility and buckling stability was investigated with changing corrugation angle, opening size and plate thickness in FE models. The results obtained showed that optimum design of these types of SPSPs, results in very desirable performance of this lateral load bearing system. Alinia et al. [18] conducted a practical guide on design of stiffeners in steel plate shear walls. Their studies included research into behavior of panels with various arrangements of transverse and longitudinal flat stiffeners. Hosseinzadeh and Tehranizadeh [19], studied the behavior of stiffened large rectangular openings in steel plate shear walls, through numerical FE analysis. The results obtained showed that, the introduction of stiffened openings increases the shear stiffness and strength and decreases the ductility ratio. Yu et al. [20], investigated the cold-formed steel framed shear wall using corrugated steel sheathing with circular holes by experimental studies. Results showed that the strength and stiffness of shear walls reduce significantly. Dastfan and Driver [21], conducted an experimental program to investigate modular SPSPs with partially encased composite columns. It was shown that the effect of modular construction on the overall behavior is negligible. According to the results obtained, they proposed design recommendations. Cao et al. [22], conducted studies on the behavior of SPSP specimens with X-shaped restrainers. Nateghi and Alavi [23], studied non-linear behavior and shear strength of steel plate shear walls with diagonal stiffeners. It was shown that the SPSP specimens with diagonally stiffeners exhibit desirable behavioral characteristics under cyclic loading. Nie et al. [24], investigated stiffened SPSWs and conducted experimental program to investigate behavior of perforated and un-perforated SPSWs and effect of changing various parameters on structural characteristics and lateral load bearing capacity of the specimens. Egorova et al. [25], conducted experimental studies of ring-shaped steel plate shear walls and proposed design recommendations to optimum design of these panels in order to obtain desirable hysteretic behavior according to the effect of various geometric parameters. Farzampour and Laman [26] also studied the performance of perforated SPSWs with corrugation pattern by conducting a parametric study and investigated the effects of plate thickness, angle of corrugation, opening size, and opening placement on the behaviour of the specimens. Also a design procedure to predict the ultimate strength of corrugated SPSWs with optimized rectangular opening position was established. Zirakian and Zhang [27], investigated structural behavior of thin SPSPs of low yield strength steel plate and studied plate-frame interaction and also effect of using low yield strength plates with low, moderate and high thickness. Qiu et al. [28], conducted experimental studies on cyclic

behavior of corrugated SPSPs. All specimens showed highly ductile behavior and stable cyclic post-buckling performance. They compared and discussed the experimental results and their implication and proposed design recommendations for seismic design of these specimens. Wang et al. [29], studied the seismic behavior of steel plate reinforced concrete composite shear walls under tension-bending-shear combined cyclic load. According to the results obtained, they proposed a design method for predicting the ultimate strength of the SPRC shear walls under applying tension-bending combined loads. Nassernia and Showkati [30], conducted experimental studies on the effects of creating opening on mid-span steel plate shear walls. They investigated the aspects of tensile-braced mid-span steel plate shear walls and the effects of circular opening on the system by theoretical and experimental studies. Results showed the acceptable behaviour of the system even in high levels of drift. Emami et al. [31,32], conducted experimental and numerical studies on cyclic behavior of trapezoidally corrugated steel shear walls. Barua and Bhowmick [33], studied nonlinear seismic performance of code designed SPSWs with opening and evaluated applicability of strip model for P-SPSWs. It was observed that using strip model to determine inelastic behavior of unstiffened P-SPSWs results in reasonable results. Berman and Bruneau [34] compared hysteretic behavior of light-gauge steel plate shear walls and braced frames. According to the results of this research it was shown that for both of the systems, the energy dissipated per cycle and the cumulative energy dissipation parameters were the same up to a ductility of four. Shariati et al. [35], studied structural performance of corrugated low yield point SPSWs with circular perforations through numerical studies. Trend of variation of shear stiffness and strength, cumulative dissipated energy and hysteretic behavior of specimens were considered in this research. According to the results obtained, it was concluded that selecting a suitable position for circular opening results in ease achievement desired performance. Berman [36], investigated the seismic behaviour of code designed steel plate shear walls using nonlinear response history analyses for ground motions. It was shown that the ratio of story shear resisted by the plate relative to the story shear resisted by the frame is between 60% and 80%. Mu and Yang [37], conducted experimental and numerical studies on seismic behavior of obliquely stiffened SPSWs with openings. Cyclic quasi-static tests on two one-bay, two-story panels were conducted. One of the specimens was multi-obliquely stiffened with one rectangular opening and the other was diagonally stiffened with two rectangular openings. Ductility, stiffness and strength degradation characteristics, energy dissipation and bearing capacity of panels were investigated and compared together. Bypour et al. [38], investigated stiffened SPSWs with rectangular opening through nonlinear finite element studies to calculate maximum shear capacity of the specimens. Parameters such as thickness, yield stress and aspect ratios of infill plates and also ratio of opening area to plate area were considered in this research. The results obtained, approved capability of response surface method to determine maximum shear capacity of SPSW specimens. Meghdadian et al. [39], investigated proposition of an

equivalent reduced thickness for composite steel plate shear walls with single opening. They also proposed a design formula to determine reduced equivalent thickness instead of creating an opening in SPSW models. Ali et al. [40], conducted numerical studies on cyclic behavior of SPSWs with differently shaped openings. They also studied the effect of using triple diagonal stiffeners on behavior of specimens. The results obtained showed that shear resistance and bearing capacity of SPSWs increase by using triple diagonal stiffeners and by increasing plate thickness. In addition, it was shown that installing triple diagonal stiffeners results in improving the cyclic behavior of perforated SPSWs.

Because of limitations of studies on SPSPs with two rectangular openings, in this research, behavior of these SPSP specimens and effect of strengthening different subpanels with various stiffener arrangements is investigated. In addition, to investigate the effect of changing the opening width on the trend of degradation shear stiffness and strength of the panel, the opening width is changed. Also, to study the effect of changing the opening height on the behavior of the whole panel, the opening height of the models is changed.

2. Introducing the FE software used

In this research, ABAQUS (2017) software [41] is used as the main platform to perform FE nonlinear static analysis. Finite element results are compared firstly against sample test results from earlier experimental studies in order to establish the validity of the proposed numerical approach. A description of the FE validation of the test specimens is provided below.

2.1. Description of experimental test specimens

Two single story, single bay SPSW panels without opening tested by Sabouri and Sajadi [5,6] have been selected for this purpose. One of the specimens was stiffened SPSP with both vertical and horizontal stiffeners and the other was unstiffened. Shear force-lateral displacement curves from the numerical studies under monotonic loading, are compared with those obtained from the experimental studies to establish the accuracy of analytical results and to validate the numerical results.

2.2. FE Modeling of experimental test specimens

The ABAQUS's four-node, doubly-curved, homogeneous, 3-dimensional continuum shell element with reduced integration (S4R) is used to model the plate and the perimeter frame as well as the stiffeners.

The stiffened and unstiffened FE models of the test specimens are depicted in figs. (1) and (2), respectively. Tables (1) and (2) present dimensions of frame members, infill plates and stiffeners. Mechanical properties of test specimens are given in table (3). A bi-linear material model with strain hardening is assumed for the boundary frame elements. The plate uses a tri-linear material model.

The stiffener connections to the boundary frame and the plate, connection of plate edges to the frame elements and connections of top beam to the columns are assumed to be

rigid. The plate and the column ends and the stiffener ends are fully restrained at the base, implying that both the horizontal and vertical stiffeners are modeled as fixed-ends elements. To prevent any instability, the FE models are restrained at the top beam against out of plane translation. The stiffener dimensions and stiffener spacing are selected according to design guidelines [42]. Transverse and longitudinal stiffeners are eccentric relative to the plate neutral plane. Nonlinear static analysis option is used. Loading is applied by subjecting the model to monotonically increasing lateral displacement until the desired drift ratio is reached. By choosing quadrilateral elements, finite membrane strains and reduced integration are selected. Quadrilateral-only mesh type is used for both the free meshing or structured meshing techniques. Mesh quality is improved by using structured meshing technique anywhere that structured meshing is allowed. Convergence criteria and mesh quality are also controlled.

Table 1: Beam and column dimensions in models

Element	Flange Width (mm)	Flange Thickness (mm)	Web Height (mm)	Web Thickness (mm)
Beam	140	20	250	20
Columns	140	15	60	20

**Table 2:** Dimensions of steel plate and stiffeners in models

Element	Width (mm)	Length (mm)	Thickness (mm)
Steel plate	1410	960	2
Vertical stiffeners	60	960	4
Horizontal stiffeners	60	1410	4

Table 3: Mechanical properties in models

| Element	Yield Stress (MPa)	Ultimate Stress (MPa)
Beam	414.9	544
Columns	414.9	544
Steel plate	192.4	288.7
Stiffeners	240	370
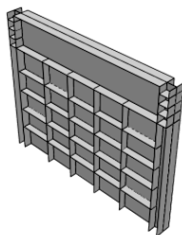
Fig. 1: FE model of experimental stiffened specimen
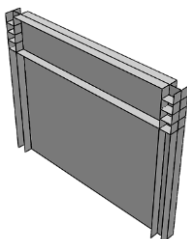
Fig. 2: FE model of experimental unstiffened specimen

2.3. Validation of FE results

Experimental and numerical results are compared in order to validate the FE model. The load-displacement graphs [5,6], as presented in fig. (3), show close agreement between the FE analysis results and the results from the tests.

(a)   Stiffened SPSP

(b)   Unstiffened SPSP
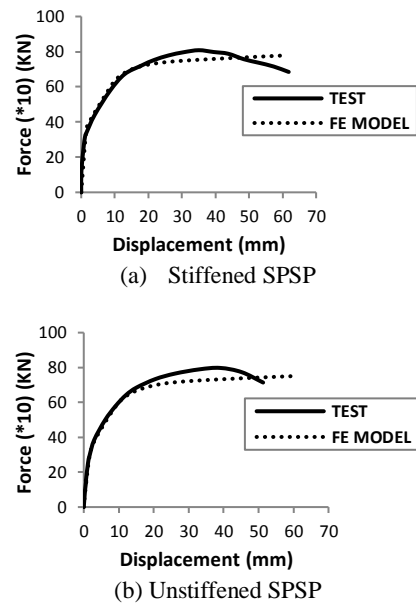
Fig. 3: Shear force–lateral displacement curves in panels

3.   Numerical investigation

3.1. Scope of study

This research is continued in two phases. In the first phase, the main purpose is to study the behavior of SPSP specimens with two rectangular openings with unstiffened and also stiffened subpanels with three different types of subpanel stiffening layouts consisting of: (1) stiffening only the subpanels at the right and left sides of the openings (the so-called corner panels, labeled as S0), (2) stiffening only the subpanels at the top and bottom levels of the openings (labeled as S1) and also (3) stiffening only the subpanels between the openings (labeled as S2), (4) stiffening both the S0 and S1 subpanels (S0&1 layout), (5) stiffening both the S0 and S2 subpanels (S0&2 layout) and also stiffening both the S1 and S2 subpanels (labeled as S1&2). In this phase of research, stiffener arrangement using three horizontal and three vertical stiffeners is used to stiff all the S0, S1, S2, S0&1, S0&2 and S1&2 procedures of stiffening subpanels.

In the second phase, by comparing the behavior of specimens with the above mentioned procedures of stiffening subpanels, the most effective stiffening procedure is selected, and then, only the effect of using various stiffener arrangements with different number of horizontal and vertical stiffeners (nine stiffener arrangements having maximum number of three stiffeners in both sides), are studied and compared with the behavior of the specimens. FE models used in both phases of the research, are analyzed and compared by changing the opening dimensions, plate thickness and also the stiffener dimensions.

3.2. Numerical modeling assumptions

The panels (stiffened and unstiffened as the case may be) are transformed into equivalent panels free from plate-frame interaction. Under this assumption, the sole function of the perimeter frame is to load transfer to the plate. In other words, any contribution of the frame to the overall stiffness and strength of the panel itself is accordingly neglected and the frame by itself can be considered as an unstable mechanism. To rationalize this approach, the frame is assumed to be rigid with pinned connections. The frame is also restrained against out-of-plane movement at the top. I-section rigid line elements are used to represent the frame members. To provide same degrees of freedom at intersections of the plate with the frame, plate edges and frame element are constrained together. Table (1) presents detailed dimensions of beam and columns used in the FE analysis. The plate and stiffener dimensions and mechanical properties of materials used are as given in tables (2) and (3) respectively. The plate is modeled using S4R shell element. The plate width, height and the thickness are chosen as 1410 mm, 960 mm and 2 mm, respectively. The plate bottom edge connection to the base is assumed fixed along its full length. The stiffeners in the stiffened plate are composed of two-sided 140 mm×4 mm steel strips, concentrically connected to the plate. Models are subjected to monotonically increasing displacement type loading, limiting the drift to 5%, in compliance with design guidelines. Modeling and analyses of panels without opening are carried out first, with the results obtained being used as a starting point for setting up the models for stiffened and unstiffened panels with openings. The opening ratios are expressed in terms of width and height ratios of the opening and the panel. The stiffened and unstiffened models are shown in fig. (4). Force-displacement curves are also shown in fig. (5). In order to improve mesh quality, structured meshing technique is used anywhere that structured meshing is allowed. Mesh verifying and mesh quality controlling is checked. Convergence criteria are also controlled. Deformed shape contours and stress contours of the specimens are also checked at the end of analysis. Shear force-lateral displacement curves of all of specimens are drawn and compared together to study the trend of variation of shear stiffness and strength of the specimens.
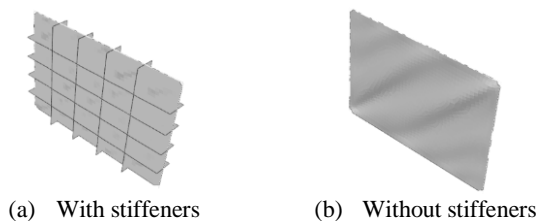

(a) With stiffeners   (b) Without stiffeners
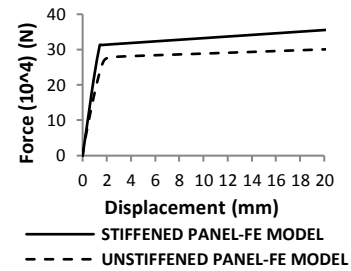
Fig. 4: Un-perforated steel plate

Fig. 5: Shear force–lateral displacement curves for steel plates in shear wall panels

3.3. Numerical modeling of the SPSP specimens with two rectangular openings

In this section, to study SPSPs with two rectangular openings, it is necessary to modify SPSP models with rigid frame with pinned connections that is generated in the previous section. So, rectangular openings with specified dimensions are created in the panels and required stiffeners are installed on the plate and around opening edges according to fig. (6). According to this fig, in SPSPs with two rectangular openings, the stiffeners are used to strengthen the plate and the opening edges. Then SPSPs are identified and are used in the next phases of research.

3.4. General characteristics of FE models of SPSPs with two rectangular openings

In the present research, behavior of SPSPs with two rectangular openings with stiffened subpanels is investigated. FE modeling of SPSP specimens is performed and trend of variation of shear stiffness and strength of the specimens are investigated. Deformed shapes of the panels are also studied. Then effect of strengthening different subpanels on the behavior of whole panels is considered. Determination of the considered stiffener arrangements is shown in fig. (7) and table (4).
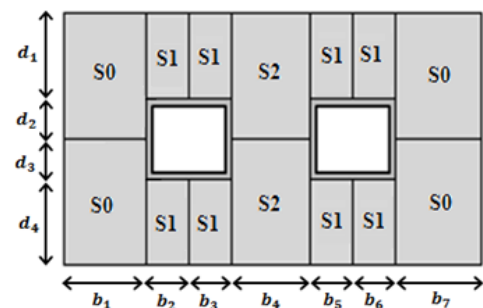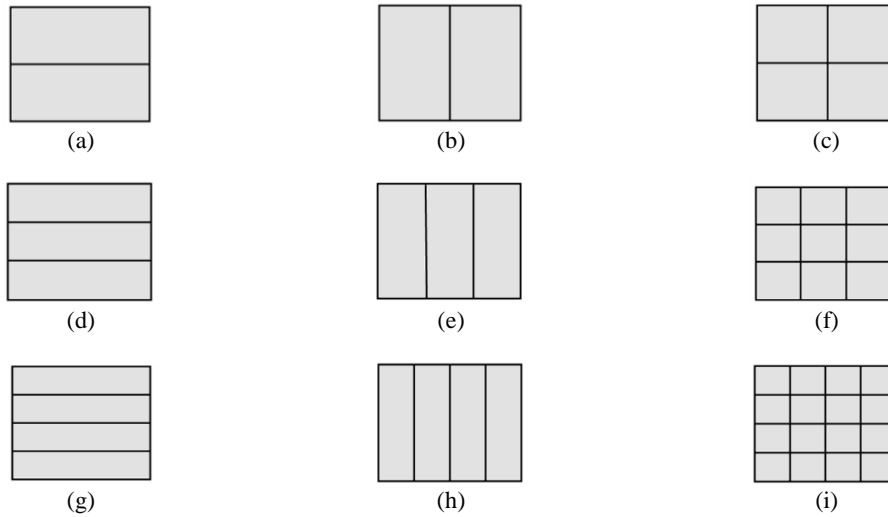

Fig. 6: Schematic layout of stiffener arrangement in SPSPs with two rectangular openings (a) Definition of subpanels (b) Parametric definition of dimensions

Fig. 7: Schematic layout of nine considered stiffener arrangements: (a) L1T0, (b) L0T1,
(c) L1T1, (d) L2T0, (e) L0T2, (f) L2T2, (g) L3T0, (h) L0T3, (i) L3T3

Table 4: Number of horizontal and vertical stiffeners of nine considered stiffener arrangements

Stiffener Arrangement	L1T0	L0T1	L1T1	L2T0	L0T2	L2T2	L3T0	L0T3	L3T3
Number of Horizontal Stiffeners	1	0	1	2	0	2	3	0	3
Number of Vertical Stiffeners	0	1	1	0	2	2	0	3	3

3.5. First series of FE models: SPSP specimens with L3T3 stiffener arrangement for stiffening all the created subpanels

In this step, behavior of SPSP specimens with two 25% rectangular openings with the unstiffened created subpanels and similar specimens with stiffened created subpanels with L3T3 stiffener arrangement is investigated and compared. Dimensions of subpanels and characteristics of the first series of FE SPSP specimens are presented in tables (5) and (6) respectively.

Table 5: Dimensions of subpanels in the first series of FE SPSP specimens

b_1 (mm)	$b_2 + b_3$ (mm)	b_4 (mm)	$b_5 + b_6$ (mm)	b_7 (mm)	d_1 (mm)	$d_2 + d_3$ (mm)	d_4 (mm)
188	422.5	189	422.5	188	325	310	325

Table 6: Characteristics of the first series of FE SPSP specimens

| Specimen Name	Opening Ratio (%)	t (mm)	t_s (mm)	h_s (mm)	Stiffener Arrangement
SSP (25%) (1,2,50)	25	1	2	50	Arrangement in fig. (6)
SSP (25%) (S0-L3T3) (1,2,50)	25	1	2	50	Stiffened S0 Panels
SSP (25%) (S1-L3T3) (1,2,50)	25	1	2	50	Stiffened S1 Panels
SSP (25%) (S2-L3T3) (1,2,50)	25	1	2	50	Stiffened S2 Panels
SSP (25%) (S0&1-L3T3) (1,2,50)	25	1	2	50	Stiffened S0 and S1 Panels
SSP (25%) (S0&2-L3T3) (1,2,50)	25	1	2	50	Stiffened S0 and S2 Panels
SSP (25%) (S1&2-L3T3) (1,2,50)	25	1	2	50	Stiffened S1 and S2 Panels

In fig. (8), out of plane deformed shape contours of panels with 1 mm thickness steel plate and two 25% openings and stiffened created subpanels are shown.
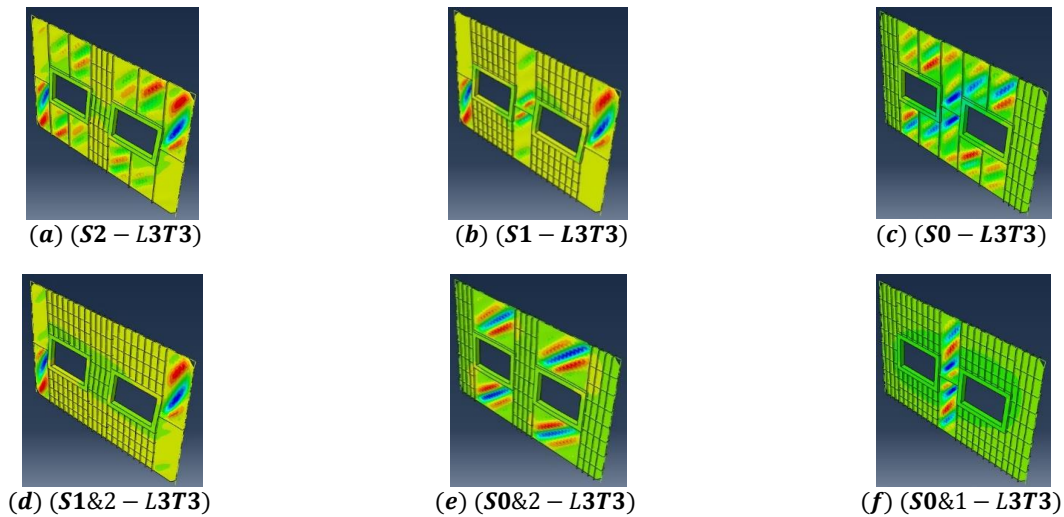
(a) ($S2 - L3T3$) (b) ($S1 - L3T3$) (c) ($S0 - L3T3$)

(d) ($S1\&2 - L3T3$) (e) ($S0\&2 - L3T3$) (f) ($S0\&1 - L3T3$)

Fig. 8: Out-of-plane deformation contours of SPSP specimens with 25% openings and 1 mm thickness plate (first series of FE SPSP specimens)

Figs. (9) to (11) show shear force-lateral displacement graphs of SPSP specimens with 1 mm thickness steel plate and two 25% openings and stiffened subpanels having L3T3 stiffener arrangements in comparison with similar SPSPs with unstiffened subpanels. In these specimens plate thickness is 1 mm. Stiffeners are also selected with 2 mm thickness and 50 mm width.
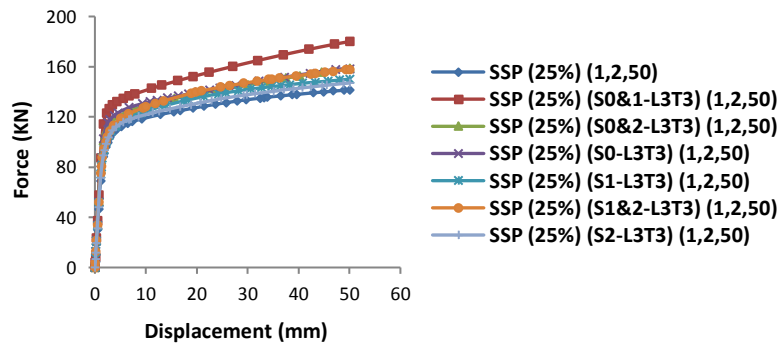
Fig. 9: Shear force-displacement graphs of SSP specimens with 1 mm thickness plate and 25% openings (first series of FE SPSP specimens)
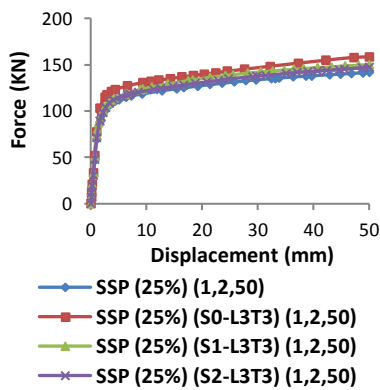
Fig. 10: Shear force-displacement graphs of first series of FE SPSP specimens (comparison of stiffening S0, S1 and S2 panels)
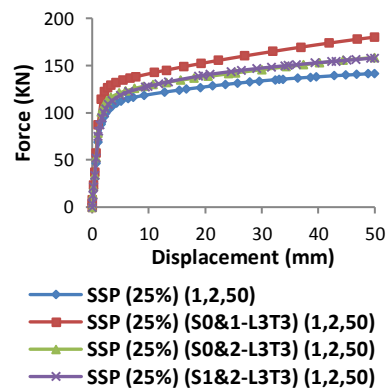
Fig. 11: Shear force-displacement graphs of first series of FE SPSP specimens (comparison of stiffening S0&1, S1&2 and S0&2 panels)

According to figs. (9) to (11), it is concluded that in SPSPs, stiffening the created subpanels with L3T3 stiffener arrangement has no effect on the shear stiffness of the specimens and also has negligible effect on the values of

shear strength of the specimens. In other words, by assuming constant plate thickness and opening dimensions in SPSP models (two 25% openings) and stiffening different subpanels around openings with various stiffener arrangements, values of shear stiffness of panels are unchanged and only shear strength of them are changed. Variation of the ratios "shear stiffness of perforated panel to shear stiffness of similar un-perforated panel" $(K_{w,r}/K_w)$, and "shear strength of perforated panel to shear strength of similar un-perforated panel" $(F_{wu,r}/F_{wu})$, versus ratio of opening width to plate width (b_{op}/b) and ratio of opening circumscribing circle diameter to plate width (D/b), for these series of models, are shown in figs. (12) to (15). In addition, it is concluded that if only one type of created subpanels is stiffened, stiffening of corner subpanels (including two subpanels at right side of right opening and two subpanels at left side of left opening called S0

subpanels), has more considerable effect on increasing stiffness and strength of whole panels in comparison with stiffening subpanels at top and bottom levels of openings (S1 subpanels) and also stiffening subpanels between two openings (S2 subpanels). Furthermore, it is concluded that using both stiffener arrangement S1&2 (stiffening subpanels S1 and S2) and arrangement S0&2 (stiffening subpanels S0 and S2), has no effect on shear stiffness and strength values of panels.
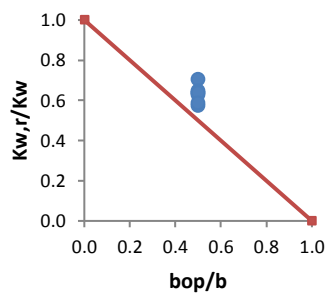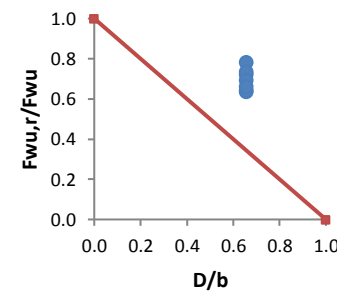

Fig. 12: Variation of the ratio of $(K_{w,r}/K_w)$ vs. (b_{op}/b) graph of first series of FE SPSP specimens
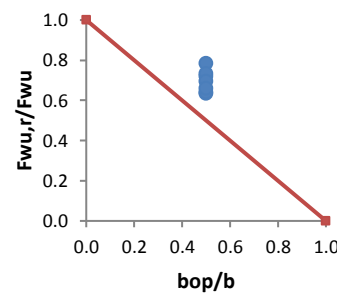
Fig. 13: Variation of the ratio of $(F_{wu,r}/F_{wu})$ vs. (b_{op}/b) graph of first series of FE SPSP specimens
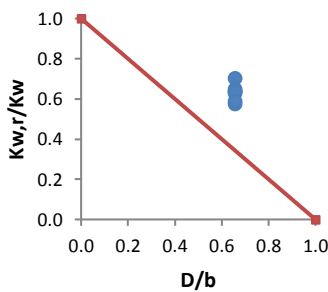
Fig. 14: Variation of the ratio of $(K_{w,r}/K_w)$ vs. (D/b) graph of first series of FE SPSP specimens

Fig. 15: Variation of the ratio of $(F_{wu,r}/F_{wu})$ vs. (D/b) graph of first series of FE SPSP specimens

3.6. Second series of FE models: SPSP specimens with different stiffener arrangements for stiffening only S0 subpanels

In the second phase of research, for the SPSP specimens with two 25% openings and 1 mm plate thickness, effect of using various stiffener arrangements to stiff S0 subpanels is investigated. Nine stiffener arrangements are used to stiff corner panels (S0):

Case 1- Arrangements with equal number of horizontal and vertical stiffeners: Arrangements L1T1, L2T2 and L3T3

with one, two and three horizontal and vertical stiffeners respectively.

Case 2- Arrangements without horizontal stiffeners: Arrangements L0T1, L0T2 and L0T3 with only one, two and three vertical stiffeners respectively.

Case 3- Arrangements without vertical stiffeners: Arrangements L1T0, L2T0 and L3T0 with only one, two and three horizontal stiffeners respectively.

Dimensions of subpanels and characteristics of the second series of FE SPSP specimens are presented in tables (7) and (8) respectively.

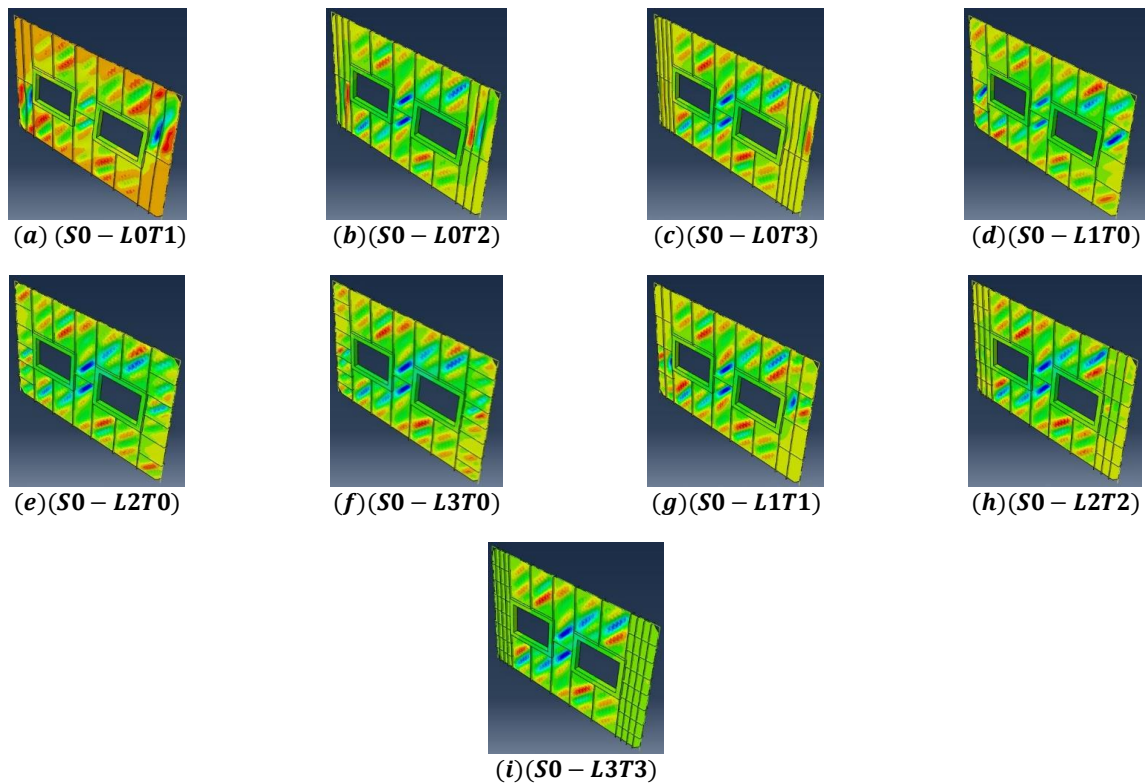**Table 7:** Dimensions of subpanels in the second series of FE SPSP specimens

b_1 (mm)	$b_2 = b_3$ (mm)	b_4 (mm)	$b_5 = b_6$ (mm)	b_7 (mm)	d_1 (mm)	$d_2 = d_3$ (mm)	d_4 (mm)
188	211.25	189	211.25	188	325	155	325

Table 8: Characteristics of the second series of FE SPSP specimens

Specimen Name	Opening Ratio (%)	t (mm)	t_s (mm)	h_s (mm)	Stiffener Arrangement
SSP (25%) (S0-L0T1) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L0T1 Arrangement
SSP (25%) (S0-L0T2) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L0T2 Arrangement
SSP (25%) (S0-L0T3) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L0T3 Arrangement
SSP (25%) (S0-L1T0) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L1T0 Arrangement
SSP (25%) (S0-L2T0) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L2T0 Arrangement
SSP (25%) (S0-L3T0) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L3T0 Arrangement
SSP (25%) (S0-L1T1) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L1T1 Arrangement
SSP (25%) (S0- L2T2) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L2T2 Arrangement
SSP (25%) (S0-L3T3) (1,2,50)	25	1	2	50	Stiffened S0 Panels with L3T3 Arrangement

Fig. (16) shows out of plane deformed shape contours of SPSP specimens.

$(a) (S0 - L0T1)$ $(b)(S0 - L0T2)$ $(c)(S0 - L0T3)$ $(d)(S0 - L1T0)$

$(e)(S0 - L2T0)$ $(f)(S0 - L3T0)$ $(g)(S0 - L1T1)$ $(h)(S0 - L2T2)$

$(i)(S0 - L3T3)$

Fig. 16: Out-of-plane deformation contours of SPSP specimens with 25% openings and 1 mm thickness plate (second series of FE SPSP specimens)

Shear force-lateral displacement graphs for SPSPs with 1 mm thickness plate and two 25% openings and with different stiffener arrangements for stiffening corner panels (S0 panels) are presented in fig. (17).
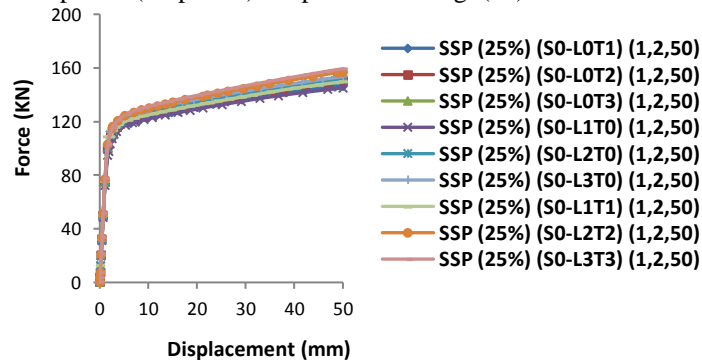
Fig. 17: Shear force-displacement graphs of SSP specimens with 1 mm thickness plate and 25% openings (second series of FE SPSP specimens)

According to this fig., using different stiffener arrangements to stiff S0 subpanels, has no effect on the values of shear stiffness of the whole panel and has negligible effect on shear strength of panels. In the case of these specimens, using L3T3 and L1T0 stiffener arrangements results in obtain maximum and minimum values of shear strength respectively. In other words, for the panels with two openings with constant opening dimensions and constant plate thickness and with different stiffener arrangements to stiff corner panels, changing the number of stiffeners in both horizontal and vertical directions in corner panels, has no

effect on shear stiffness of the whole panel and also its effect on shear strength of whole panel is negligible. In these conditions, by using L3T3 and L1T0 stiffener arrangements maximum and minimum values of shear strength of whole panel are obtained respectively.

Trend of variation of the ratios of shear stiffness, $(K_{w,r}/K_w)$, and shear strength, $(F_{wu,r}/F_{wu})$, vs. the ratios of (b_{op}/b) and (D/b), for these series of models are shown in figs. (18) to (21).
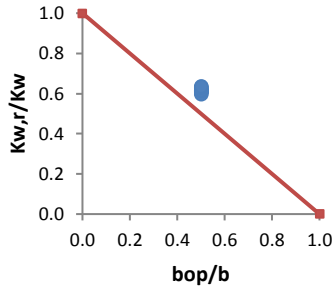

Fig. 18: Variation of the ratio of $(K_{w,r}/K_w)$ vs. (b_{op}/b) graph of second series of FE SPSP specimens
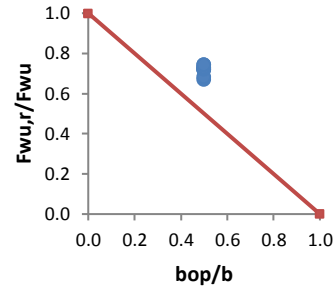

Fig. 19: Variation of the ratio of $(F_{wu,r}/F_{wu})$ vs. (b_{op}/b) graph of second series of FE SPSP specimens
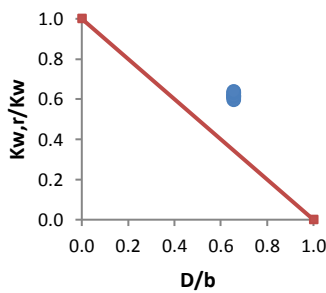

Fig. 20: Variation of the ratio of $(K_{w,r}/K_w)$ vs. (D/b) graph of second series of FE SPSP specimens
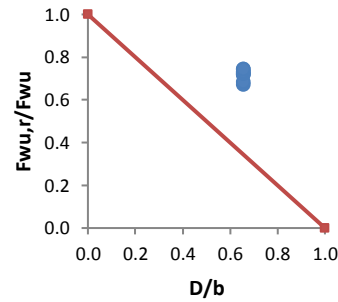

Fig. 21: Variation of the ratio of $(F_{wu,r}/F_{wu})$ vs. (D/b) graph of second series of FE SPSP specimens

3.7. Third series of FE models: FE models of SPSP specimens with variable opening width and constant opening height

Effect of changing opening width in SPSPs with constant opening height, is studied in this section. In these series of models opening height is equal to 450 mm and opening widths are equal to 200 mm, 250 mm, 300 mm and 350 mm.

Dimensions of subpanels and characteristics of the third series of FE SPSP specimens are presented in tables (9) and (10) respectively.
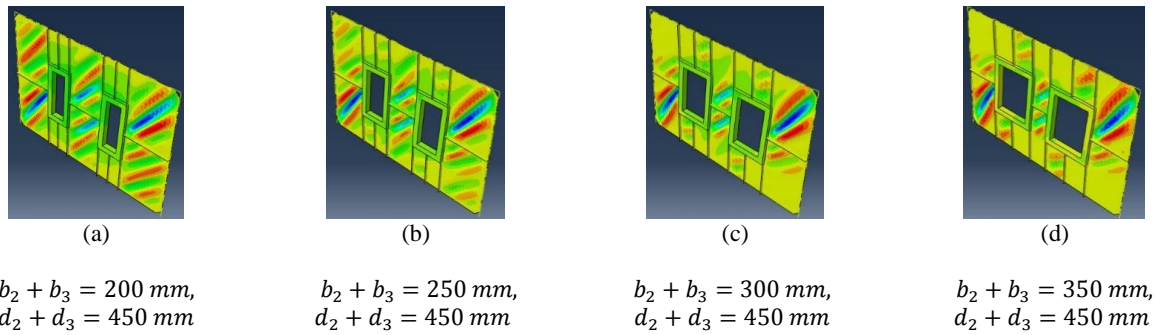
Table 9: Dimensions of subpanels in the third series of FE SPSP specimens ($b_1 = b_7, b_2 = b_6$)

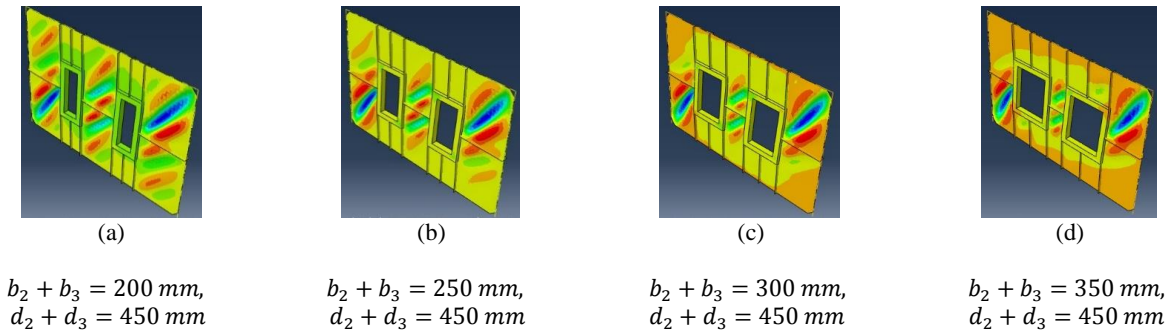| b_1 (mm)	b_2 (mm)	$b_3 + b_4 + b_5$ (mm)	b_6 (mm)	b_7 (mm)	d_1 (mm)	$d_2 = d_3$ (mm)	d_4 (mm)
Variable	Variable	500	Variable	Variable	255	225	255

Table 10: Characteristics of the third series of FE SPSP specimens
$(b_2 = b_3 = b_5 = b_6)$ and $(d_2 = d_3)$ and $(d_1 = d_4)$ and $(b_1 = b_7)$

Specimen Name	$b_2 + b_3$ (mm)	$d_2 + d_3$ (mm)	t (mm)	t_s (mm)	h_s (mm)
SSP (200*450) (1,2,50)	200	450	1	2	50
SSP (250*450) (1,2,50)	250	450	1	2	50
SSP (300*450) (1,2,50)	300	450	1	2	50
SSP (350*450) (1,2,50)	350	450	1	2	50
SSP (200*450) (2,3,50)	200	450	2	3	50
SSP (250*450) (2,3,50)	250	450	2	3	50
SSP (300*450) (2,3,50)	300	450	2	3	50
SSP (350*450) (2,3,50)	350	450	2	3	50
SSP (200*450) (3,4,50)	200	450	3	4	50
SSP (250*450) (3,4,50)	250	450	3	4	50
SSP (300*450) (3,4,50)	300	450	3	4	50
SSP (350*450) (3,4,50)	350	450	3	4	50

Out of plane deformed shape contours of the third series of panels are presented in figs. (22) to (24).

(a)   (b)   (c)   (d)

$b_2 + b_3 = 200\ mm,$ $b_2 + b_3 = 250\ mm,$ $b_2 + b_3 = 300\ mm,$ $b_2 + b_3 = 350\ mm,$
$d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$

Fig. 22: Out-of-plane deformation contours of specimens with 1 mm thickness plate and two openings with constant height and variable width (third series of FE SPSP specimens)

(a)   (b)   (c)   (d)

$b_2 + b_3 = 200\ mm,$ $b_2 + b_3 = 250\ mm,$ $b_2 + b_3 = 300\ mm,$ $b_2 + b_3 = 350\ mm,$
$d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$

Fig. 23: Out-of-plane deformation contour of specimens with 2 mm thickness plate and two openings with constant height and variable width (third series of FE SPSP specimens)

(a)   (b)   (c)   (d)

$b_2 + b_3 = 200\ mm,$ $b_2 + b_3 = 250\ mm,$ $b_2 + b_3 = 300\ mm,$ $b_2 + b_3 = 350\ mm,$
$d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$ $d_2 + d_3 = 450\ mm$
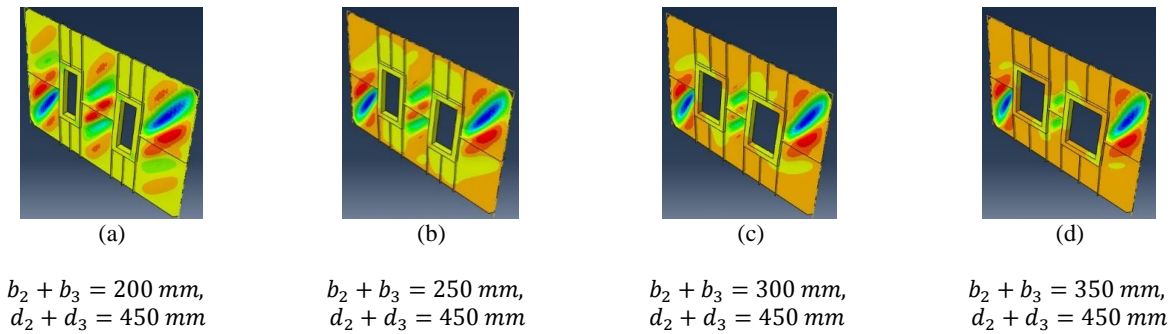
Fig. 24: Out-of-plane deformation contour of specimens with 3 mm thickness plate and two openings with constant height and variable width (third series of FE SPSP specimens)

Shear force-lateral displacement graphs of SPSPs with constant height and variable width are presented in fig. (25).
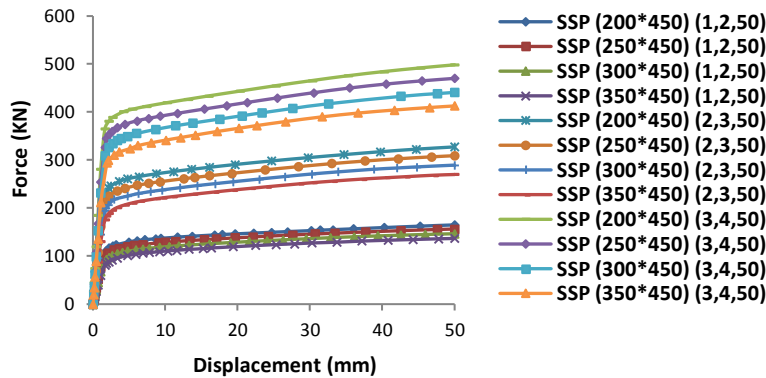

Fig. 25: Shear force-lateral displacement graphs of the SPSP specimens with two openings
and constant height and variable width (third series of FE SPSP specimens)

According to the results obtained, for SPSPs with constant height and variable width, it is concluded that by assuming constant plate thickness, increasing opening width decreases shear stiffness and strength of panels considerably. In addition, with assumption of constant opening dimensions in SPSPs with variable plate thickness, increasing plate thickness results in an increase in shear stiffness and strength of panels. In addition, it is shown that by increasing plate thickness, discrepancy of shear stiffness and strength of panels with two openings with constant height and variable width, increases.

Comparison of graphs presenting ratio of $\left(K_{w,r}/K_w\right)$ and $\left(F_{wu,r}/F_{wu}\right)$ vs. the ratios of $\left(b_{op}/b\right)$ and (D/b) are shown in figs. (26) to (29). It is shown that, using the $\left(b_{op}/b\right)$ ratio or in other words, using the "effective width" parameter to calculate the trend of variation of shear stiffness and shear strength ratios of the third series of specimens, leads reasonable results. "Effective width" parameter in perforated SPSPs is introduced as the subtraction of "summation of width of two openings" from the total panel width.
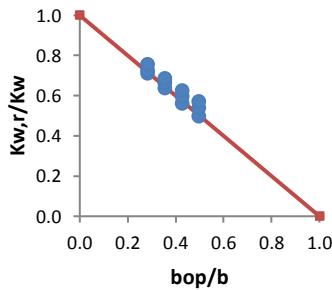

Fig. 26: Variation of the ratio of $\left(K_{w,r}/K_w\right)$ vs. $\left(b_{op}/b\right)$ graph of third series of FE SPSP specimens

Fig. 27: Variation of the ratio of $\left(F_{wu,r}/F_{wu}\right)$ vs. $\left(b_{op}/b\right)$ graph of third series of FE SPSP specimens
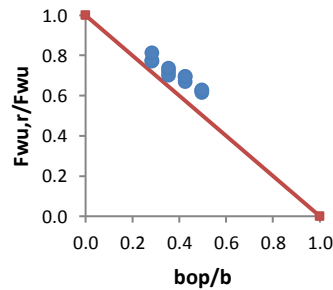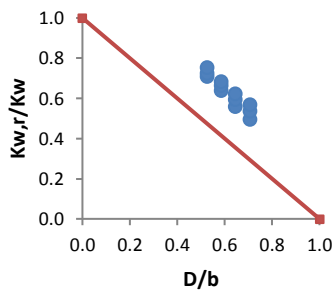

Fig. 28: Variation of the ratio of $\left(K_{w,r}/K_w\right)$ vs. (D/b) graph of third series of FE SPSP specimens
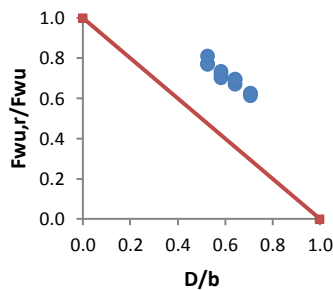

Fig. 29: Variation of the ratio of $\left(F_{wu,r}/F_{wu}\right)$ vs. (D/b) graph of third series of FE SPSP specimens

3.8. Fourth series of FE models: FE models of SPSP specimens with variable opening height and constant opening width

Effect of changing opening height in SPSPs with constant opening width, is studied in this section. In these series of models opening width is equal to 250 mm and opening heights are equal to 300 mm, 350 mm, 400 mm and 450 mm. Dimensions of subpanels and characteristics of the fourth series of FE SPSP specimens are presented in tables (11) and (12) respectively.
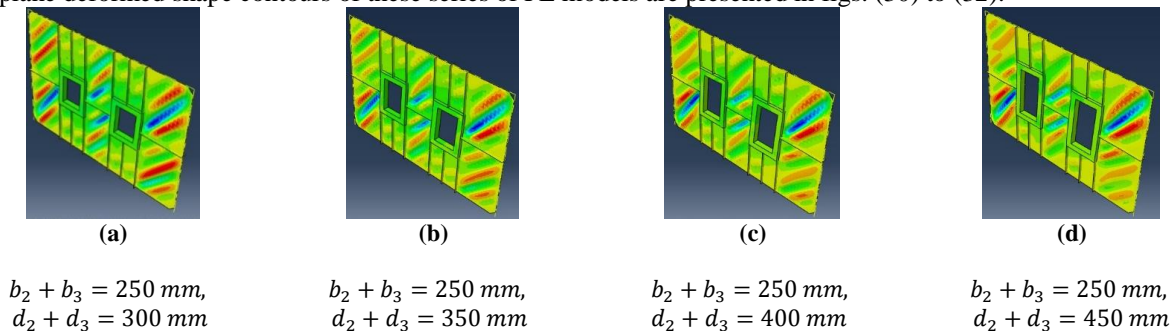
Table 11: Dimensions of subpanels in the fourth series of FE SPSP specimens

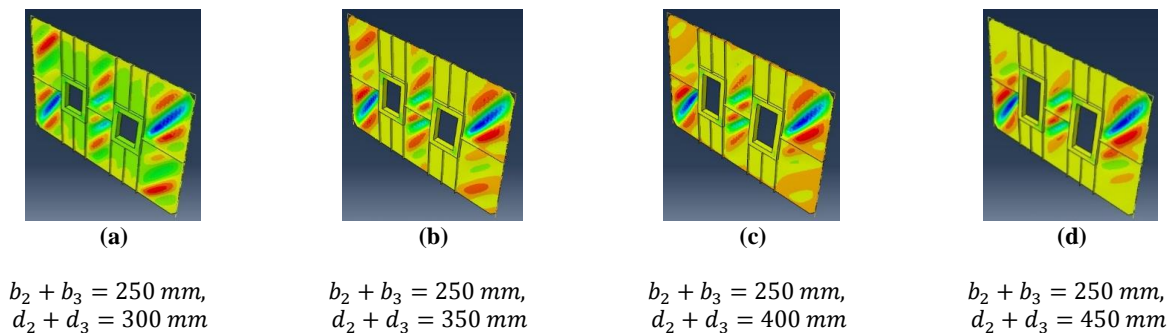| b_1 (mm)	$b_2 = b_3$ (mm)	b_4 (mm)	$b_5 = b_6$ (mm)	b_7 (mm)	d_1 (mm)	$d_2 = d_3$ (mm)	d_4 (mm)
330	125	250	125	330	Variable	Variable	Variable

Table 12: Characteristics of the fourth series of FE SPSP specimens $(b_2 = b_3 = b_5 = b_6)$ and $(d_2 = d_3)$ and $(d_1 = d_4)$ and $(b_1 = b_7)$

Specimen Name	$b_2 + b_3$ (mm)	$d_2 + d_3$ (mm)	t (mm)	t_s (mm)	h_s (mm)
SSP (250*300) (1,2,50)	250	300	1	2	50
SSP (250*350) (1,2,50)	250	350	1	2	50
SSP (250*400) (1,2,50)	250	400	1	2	50
SSP (250*450) (1,2,50)	250	450	1	2	50
SSP (250*300) (2,3,50)	250	300	2	3	50
SSP (250*350) (2,3,50)	250	350	2	3	50
SSP (250*400) (2,3,50)	250	400	2	3	50
SSP (250*450) (2,3,50)	250	450	2	3	50
SSP (250*300) (3,4,50)	250	300	3	4	50
SSP (250*350) (3,4,50)	250	350	3	4	50
SSP (250*400) (3,4,50)	250	400	3	4	50
SSP (250*450) (3,4,50)	250	450	3	4	50

Out of plane deformed shape contours of these series of FE models are presented in figs. (30) to (32).

(a)	(b)	(c)	(d)
$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 300\ mm$	$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 350\ mm$	$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 400\ mm$	$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 450\ mm$

Fig. 30: Out-of-plane deformation contours of specimens with 1 mm thickness plate and two openings with constant width and variable height (fourth series of FE SPSP specimens)

(a)	(b)	(c)	(d)
$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 300\ mm$	$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 350\ mm$	$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 400\ mm$	$b_2 + b_3 = 250\ mm,$ $d_2 + d_3 = 450\ mm$

Fig. 31: Out-of-plane deformation contours of specimens with 2 mm thickness plate and two openings with constant width and variable height (fourth series of FE SPSP specimens)

(a) | **(b)** | **(c)** | **(d)**

$b_2 + b_3 = 250\ mm,$ | $b_2 + b_3 = 250\ mm,$ | $b_2 + b_3 = 250\ mm,$ | $b_2 + b_3 = 250\ mm,$
$d_2 + d_3 = 300\ mm$ | $d_2 + d_3 = 350\ mm$ | $d_2 + d_3 = 400\ mm$ | $d_2 + d_3 = 450\ mm$
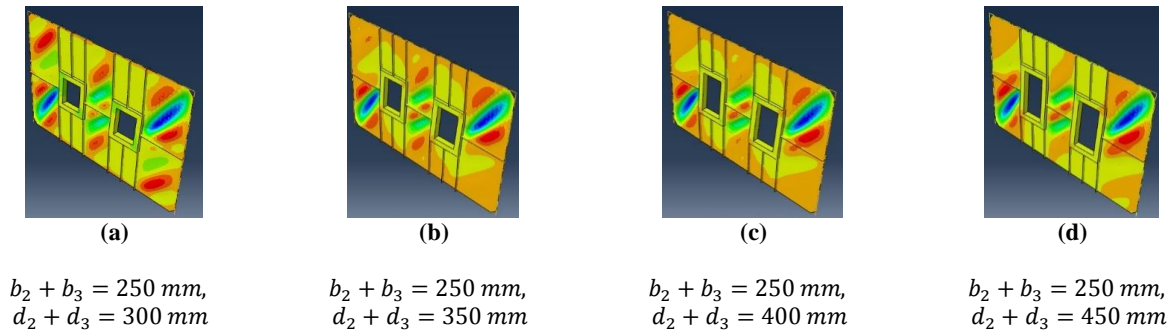
Fig. 32: Out-of-plane deformation contours of specimens with 3 mm thickness plate and two openings with constant width and variable height (fourth series of FE SPSP specimens)

Shear force-lateral displacement graphs for SPSPs with two openings with constant width and variable height are shown in fig. (33).
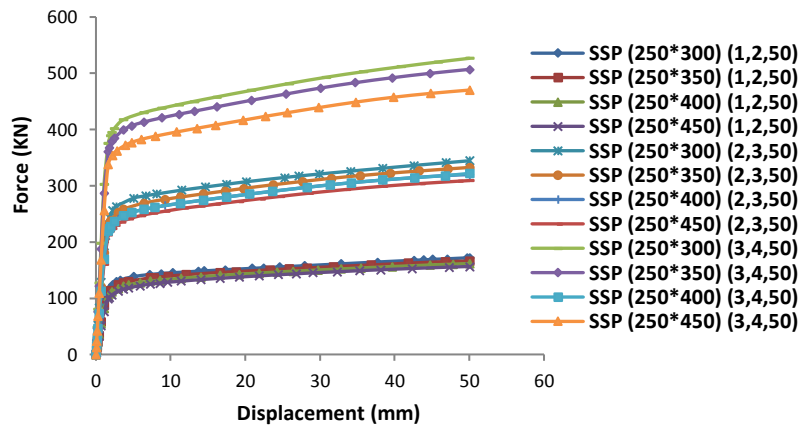

Fig. 33: Shear force-lateral displacement of the SPSP specimens with two openings with constant width and variable height (fourth series of FE SPSP specimens)

By comparison of shear force-lateral displacement graphs of SPSPs with openings with constant width and variable height, it is shown that for SPSPs with constant thickness, increasing opening height results in increase of shear stiffness and strength of panels negligibly. In addition, if opening dimensions are assumed constant with variable plate thickness, by increasing plate thickness shear stiffness and strength of panels increases. Also, it is concluded that increasing plate thickness of panels, causes an increase in discrepancy of values of shear stiffness and strength of

panels with two openings with constant width and variable height. Comparison of graphs presenting ratio of $(K_{w,r}/K_w)$ and $(F_{wu,r}/F_{wu})$ vs. ratio of (b_{op}/b) and (D/b) are shown in figs. (34) to (37). According to the results obtained, using the (b_{op}/b) ratio or "effective width" parameter to calculate trend of variation of shear stiffness and shear strength ratios of the fourth series of specimens, is recommended.
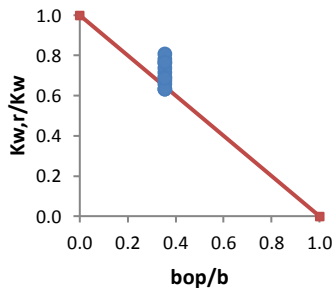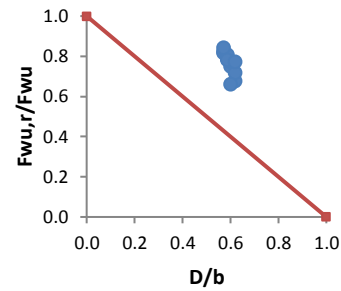

Fig. 34: Variation of the ratio of $(K_{w,r}/K_w)$ vs. (b_{op}/b) graph of fourth series of FE SPSP specimens
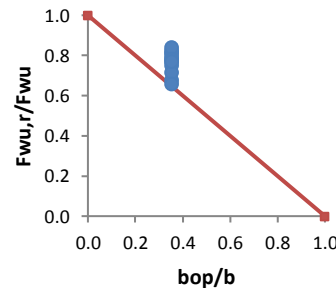
Fig. 35: Variation of the ratio of $(F_{wu,r}/F_{wu})$ vs. (b_{op}/b) graph of fourth series of FE SPSP specimens
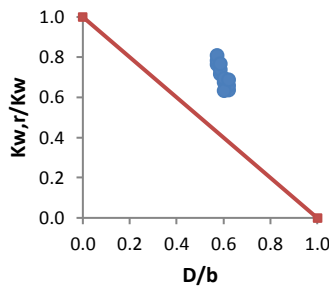
Fig. 36: Variation of the ratio of $\left(K_{w,r}/K_w\right)$ vs. (D/b) graph of fourth series of FE SPSP specimens

Fig. 37: Variation of the ratio of $\left(F_{wu,r}/F_{wu}\right)$ vs. (D/b) graph of fourth series of FE SPSP specimens

3.9. Comparison of the results obtained from sections 3.7 and 3.8

By assuming constant plate thickness for panels with two openings, if opening height is constant and opening width is variable, increasing the opening width decreases the values of shear stiffness and shear strength of the panel considerably. In the case of panels with constant opening width and variable opening height, increasing opening height decreases the values of shear strength and stiffness of the panel negligibly. According to the results obtained, it is shown that in SPSPs with two rectangular openings and without additional stiffeners to strengthen the created subpanels, it is recommended to use the ratio of "opening width to the plate width" or in other words, the "effective width" parameter to determine the trend of variation of ratios of "shear strength of the perforated panel to shear strength of similar un-perforated panel" and "shear stiffness of the perforated panel to shear stiffness of similar un-perforated panel". "Effective width" parameter in this research is introduced as the subtraction of "summation of width of two openings" from the total panel width.

4. Conclusions

In the present research, behavior of SPSPs with two rectangular openings and stiffened different subpanels around openings is investigated. Various stiffener arrangements are used for stiffening subpanels in this research. To study the effect of stiffening subpanels on the behavior of the whole panel, other parameters such as opening dimensions, plate thickness and stiffener dimensions remain unchanged and only the layout of stiffener arrangement to strengthen subpanels is changed. In the next step, for studying the effect of changing opening width on the variation of shear strength and stiffness of panels by complying with stiffener arrangement, plate thickness and opening height and also stiffeners dimensions remain unchanged, and only the opening width is changed in models. In the third step, to investigate the effect of changing opening height on behavior of whole panels with keeping other parameters unchanged, only opening height of models is changed. The results obtained by this research work are summarized as follows:

1- If only one type of created subpanels is stiffened, stiffening of corner subpanels (including two subpanels at right side of right opening and two subpanels at left side of left opening called S0 subpanels), has more considerable effect on increasing stiffness and strength of whole panels in comparison with stiffening subpanels at top and bottom levels of openings (S1 subpanels) and also stiffening subpanels between two openings (S2 subpanels).

2- In other words, for panels with two openings with constant opening dimensions and constant plate thickness with different stiffener arrangements to stiff corner panels, changing the number of stiffeners in both horizontal and vertical directions in corner panels, has no effect on shear stiffness of the whole panel and its effect on shear strength of the whole panel is also negligible. In these conditions, by using L3T3 and L1T0 stiffener arrangements, maximum and minimum values of shear strength of whole panel are obtained respectively.

3- By assumption of constant plate thickness in SPSPs with openings with constant height and variable width, increasing opening width results in decrease shear stiffness and strength considerably. In addition, with the assumption of constant opening dimension and variable plate thickness, increasing plate thickness results in increase in shear stiffness and strength of panels. Also, it is showed that by increasing plate thickness, discrepancy of values of shear strength and stiffness of models with openings with constant height and variable width are increased.

4- With the assumption of investigating perforated panels with constant plate thickness and two openings with constant width and variable height, by increasing the opening height, shear stiffness and strength values decrease negligibly. In addition, with assumption of constant opening dimensions, values of stiffness and strength of the whole panel increase by increasing the plate thickness. In addition, it is concluded that by increasing plate thickness, discrepancy of shear stiffness and strength values of SPSPs with two openings with constant width and variable height is increased.

5- By introducing the "effective width" parameter as the subtraction of "summation of width of two

openings" from the total panel width, in this research, it is concluded that in SPSPs with two rectangular openings and without stiffened created subpanels, using the ratio of "opening width to the plate width" or in other words, the "effective width" parameter to determine the trend of variation of ratios of "shear strength of the perforated panel to shear strength of similar un-perforated panel" and "shear stiffness of the perforated panel to shear stiffness of similar un-perforated panel", obtains reasonable results.

In addition, it is concluded from this research that:

o For the SPSP specimens with constant opening dimensions and also constant subpanel dimensions and stiffener arrangement with three horizontal and three vertical stiffeners to strengthen various subpanels (first series of models), the minimum and maximum values of the ratio of $K_{w,r}/K_w$ are equal to 0.57 and 0.7, respectively. In the case of the ratio of $F_{wu,r}/F_{wu}$, the minimum and maximum values are 0.64 and 0.78, respectively.

o In the case of SPSPs with constant opening dimensions and also constant subpanel dimensions and various stiffener arrangements to stiff corner subpanels (S0 subpanels) (second series of models), the minimum and maximum values of the ratio of $K_{w,r}/K_w$ are equal to 0.61 and 0.63, respectively. In addition, the minimum and maximum values of the ratio of $F_{wu,r}/F_{wu}$, are equal to 0.67 and 0.72, respectively.

o For the SPSP specimens with variable opening width and constant opening height (third series of specimens), the minimum and maximum values of the ratio of $K_{w,r}/K_w$ are equal to 0.5 and 0.75, respectively. Also, in the case of the ratio of $F_{wu,r}/F_{wu}$, the minimum and maximum values are equal to 0.62 and 0.81, respectively.

o In the case of SPSP specimens with variable opening height and constant opening width, the minimum and maximum values of the ratio of $K_{w,r}/K_w$ in the fourth series of specimens are equal to 0.64 and 0.81, respectively. In addition, the minimum and maximum values of the ratio of $F_{wu,r}/F_{wu}$, are equal to 0.68 and 0.82, respectively.

References

[1] Sabouri-Ghomi, S., Roberts, T.M. 1991. Hysteretic characteristics of unstiffened plate shear panels. *Journal of Thin-Walled Structures,* 12(2), pp. 145-162.

[2] Sabouri-Ghomi, S., Roberts, T.M. 1992. Hysteretic characteristics of unstiffened perforated plate shear panels. *Journal of Thin-Walled Structures,* 14(2), pp.139-151.

[3] Sabouri-Ghomi, S., Ventura, C.E., Kharrazi, M.H.K. 2005. Shear analysis and design of ductile steel plate walls. *ASCE Journal of Structural Engineering*, 131(6), pp. 878-889.

[4] Sabouri-Ghomi, S. 2002. *Lateral load resisting systems: An introduction to Steel Plate Shear Walls*. 1st Edition. Tehran, Iran: Angizeh Publishing Company.

[5] Sabouri-Ghomi, S., Sajadi, R. 2012. Experimental and theoretical studies of steel shear walls with and without stiffeners. *Journal of Constructional Steel Research,* 75, pp.152–159.

[6] Sajadi, S.R.A. 2009. Behavior of steel plate shear walls with opening. (PhD dissertation). Khajeh Nasir Toosi University of Technology, Tehran, Iran.

[7] Sabouri-Ghomi, S., Mamazizi, S. 2015. Experimental investigation on stiffened steel plate shear walls with two rectangular openings. *Journal of Thin-Walled Structures*, 86, pp. 56-66.

[8] Vian, D., Bruneau, M., Purba, R. 2009.Special perforated steel plate shear walls with reduced beam section anchor beams. II: analysis and design recommendations. *ASCE Journal of Structural Engineering,* 135(3), pp. 221-228

[9] Purba, R., Bruneau, M. 2009. Finite-element investigation and design recommendations for perforated steel plate shear walls. *ASCE Journal of Structural Engineering*, 135(11), pp.1367-1376.

[10] Chan, R., Albermani, F., Kitipornchai, S. 2011. Stiffness and strength of perforated steel plate shear wall. *Journal of Procedia Engineering*, 14, pp. 675–679.

[11] Ding, Y., Deng, E.F., Zong, L., Dai, X.M., Lou, N., Chen, Y. 2017. Cyclic tests on corrugated steel plate shear walls with openings in modularized-constructions. *Journal of Constructional Steel Research,* 138, pp. 675-691.

[12] Bhowmick, A.K., Grondin, G.Y., Driver, R.G. 2014. Nonlinear seismic analysis of perforated steel plate shear wall. *Journal of Constructional Steel Research,* 94, pp. 103-113.

[13] Mu, Z., Yang, Y. 2020. Experimental and numerical study on seismic behavior of obliquely stiffened steel plate shear walls with openings. *Journal of Thin-Walled Structures,* 146, 106457.

[14] Moghimi, H., Driver, R.G. 2014. Column demands in steel plate shear walls with regular perforations using performance-based design methods. *Journal of Constructional Steel Research,* 103, pp. 13-22.

[15] Choi, I.R., Park, H.G. 2009. Steel plate shear walls with various infill plate designs. *ASCE Journal of Structural Engineering,* 135(7), pp. 785-796.

[16] Shekastehband, B., Azarakhsh, A.A., Showkati, H. 2017. Hysteretic behavior of perforated steel plate shear walls with beam-only connected infill plates. *Journal of Steel and composite Structures*, 25(4), pp. 505-521.

[17] Bahrebar, M., Zirakian, T., Hajsadeghi, M. 2015. Nonlinear buckling analysis of steel plate shear walls with trapezoidally corrugated and perforated infill plates. *Proceeding of Annual Stability Conference Structural Stability Research Council*, Nashville, Tennessee, March 24-27, 2015.

[18] Alinia, M.M., Sarraf Shirazi, R. 2009. On the design of stiffeners in steel plate shear walls. *Journal of Constructional Steel Research*, 65, pp. 2069-2077.

[19] Hosseinzadeh, S.A.A., Tehranizadeh, M. 2012. Introduction of stiffened large rectangular openings in steel plate shear walls. *Journal of Constructional Steel Research*, 77, pp. 180–192.

[20] Yu, C., Yu, G. 2016. Experimental investigation of cold-formed steel framed shear wall using corrugated steel sheathing with circular holes. *ASCE Journal of Structural Engineering,* 142(12), 04016126.

[21] Dastfan, M., Driver, R. 2016. Large-scale test of a modular steel plate shear wall with partially encased composite columns. *ASCE Journal of Structural Engineering,* 142(2): 04015142.

[22] Cao, Z., Wang, Z., Du, P., Liu, H., Fan, F. 2019. Research on steel plate shear walls stiffened with X-Shaped restrainers: hysteretic behavior and effect of height-to-thickness ratio of steel plate. *Journal of Thin-Walled Structures*, 144 (6), 106316.

[23] Nateghi, F., Alavi, E. 2009. Non-linear behavior and shear strength of diagonally stiffened steel plate shear walls. International Journal of Engineering, 22, pp. 343-356.

[24] Nie, J.G., Zhu, L., Fan, J.S., Mo, Y.L. 2013. Lateral resistance capacity of stiffened steel plate shear walls. *Journal of Thin-Walled Structures*, 67, pp. 155-167.

[25] Egorova, N., Eatherton, M., Maurya, M. 2014. Experimental study of ring-shaped steel plate shear walls. *Journal of Constructional Steel Research*, 103, pp. 179–189.

[26] Farzampour, A., Laman, J.A. 2015. Behavior prediction of corrugated steel plate shear walls with openings. *Journal of Constructional Steel Research*, 114, pp. 258-268.

[27] Zirakian, T., Zhang, J. 2015. Structural performance of unstiffened low yield point steel plate shear walls. *Journal of Constructional Steel Research,* 112, pp. 40-53.

[28] Qiu, J., Zhao, Q., Yu, C., Li, Z. 2018. Experimental studies on cyclic behavior of corrugated steel plate shear walls. *ASCE Journal of Structural Engineering,* 144(11): 04018200.

[29] Wang, J.J., Tao, M.X., Fan, J.S., Nie, X. 2018. Seismic behavior of steel plate reinforced concrete composite shear walls under tension-bending-shear combined cyclic load. *ASCE Journal of Structural Engineering,* 144(7), 04018075.

[30] Nassernia, S., Showkati, H. 2017. Experimental study of opening effects on mid-span steel plate shear walls. *Journal of Constructional Steel Research,* 137, pp. 8-18.

[31] Emami, F., Mofid, M., Vafai, A. 2013. Experimental study on cyclic behavior of trapezoidally corrugated steel shear walls. *Journal of Engineering Structures,* 48, pp. 750-762.

[32] Emami, F., Mofid, M. 2014. On the hysteretic behavior of trapezoidally corrugated steel shear walls. *Journal of the Structural Design of Tall and Special Buildings*, 23(2), pp. 94-104.

[33] Barua, K., Bhowmick, A.K. 2019. Nonlinear seismic performance of code designed perforated steel plate shear walls. *Journal of Steel and Composite Structures*, 31(1), pp. 85-98.

[34] Berman, J.W., Bruneau, M. 2005. Comparing hysteretic behavior of light-gauge steel plate shear walls and braced frames. *Journal of Engineering Structures,* 27, pp. 475-485.

[35] Shariati, M., Safaei Faegh, S., Mehrabi, P., Bahavarnia, M., Zandi, Y., Rezaee Masoom, D., Toghroli, A., Trung, N.T., Salih, M. 2019. Numerical study on the structural performance of corrugated low yield point steel plate shear walls with circular openings. *Journal of Steel and Composite Structures,* 33(4), pp. 569-581.

[36] Berman, JW. 2011. Seismic behavior of code designed steel plate shear walls. *Journal of Engineering Structures*, 33(1), pp. 230-244.

[37] Mu, Z., Yang, Y. 2020. Experimental and numerical study on seismic behavior of obliquely stiffened steel plate shear walls with openings. *Journal of Thin-walled Structures,* 146, 106457.

[38] Bypour, M., Kioumarsi, M., Yekrangnia, M. 2021 Shear capacity prediction of stiffened steel plate shear walls (SSPSW) with openings using response surface method. *Journal of Engineering Structures,* 226, 111340.

[39] Meghdadian, M., Gharaei, M., Arabshahi, A., Mahdavi, N., Ghalenovi, M. 2020. Proposition of an equivalent reduced thickness for composite steel plate shear walls containing an opening. *Journal of Constructional Steel Research,* 168, 105985.

[40] Ali, M.M., Osman, S.A., Husam, O.A., Al Zand, A.W. 2018. Numerical study of the cyclic behavior of steel plate shear wall systems (SPSWs) with differently shaped openings. *Journal of Steel and Composite Structures*, 26(3), pp. 361-373.

[41] Hibbitt, Karlsson, and Sorenson, Inc. (HKS). 2017. ABAQUS/standard users' manual, Hibbitt, Karlsson, and Sorenson, Inc., Pawtucket, R.I.

[42] Sabouri-Ghomi, S., Kharrazi, M.H.K., Mamazizi, S., Sajadi, R. Buckling behavior improvement of steel plate shear wall systems. *Journal of the Structural Design of Tall and Special Buildings*, 17(4), pp. 823-837.