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# Introduction of stiffened large rectangular openings in steel plate shear walls

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ABSTRACT

The nonlinear behavior of steel plate shear walls (SPSWs) with stiffened large rectangular openings used as windows or doors in buildings is studied. A number of SPSWs with and without openings are numerically analyzed, and the results are utilized (a) to characterize the behavior of SPSWs with the openings, (b) to study the effects of various opening features as well as size of local boundary elements (LBE) around the opening and thickness of infill plates on either side of the opening and (c) to investigate the changes in the system strength, stiffness and ductility due to the introduction of the openings. Results show that the procedure addressed by AISC Design Guide 20 for design of beams above and below the opening level is not perfect. Use of thicker or thinner infill plates or weaker profiles for the LBE can alter the yielding sequence in the system. Notably, the type, location and geometry of stiffened openings are not influential themselves on the system strength, although different LBE sizes required for different openings may have some effects. The introduction of stiffened openings in different SPSWs increases both the ultimate strength and stiffness, while somewhat decreases the ductility ratio.



## 1. Introduction

Steel plate shear walls (SPSWs) have been increasingly utilized as a lateral force resisting system, which resist both earthquake and wind forces. This structural system has been used in significant buildings beginning decades ago, and implementation has accelerated since the recent years [1]. They provide an effective and economical solution for new construction as well as retrofitting of existing structures. A conventional SPSW consists of thin stiffened or unstiffened steel plates surrounded by horizontal and vertical boundary elements (HBE and VBE) that can be multiple stories high and one or more bays wide.

Early designs of SPSWs were based on the concept of preventing shear buckling in the infill plate by using either thick infill plate or by adding stiffeners to the infill plate, but in recent years, the idea of utilizing the post-buckling strength with the use of thin unstiffened infill plate has gained wide acceptance from researchers and designers globally. Typical SPSW has slender infill plates that are capable of resisting large tension forces by developing diagonal tension fields in the infill plate, but little or no compression. They should be expected to buckle under very small lateral loads or even considered pre-buckled under their own weight prior to loading. It is known that plastic deformations in SPSWs should primarily be provided by the infill plates [1,2] and that the boundary members should be designed so as to develop the full tension strength of the infill panels.

Numerous research programs and large-scale experiments have been shown that this system possesses high level of initial stiffness, strength, ductility and robustness under cyclic loading [3–12]. SPSWs offer significant advantages over many other lateral load-resisting systems in terms of foundation cost, saving steel, performance, ease of design, speed and simplicity of construction and usable space in buildings [1,13]. They can also be accommodated to allow different types of openings within their infill plates.

To date, experimental and analytical research on thin unstiffened SPSWs is mainly focused on the behavior of SPSWs with solid infill plates (i.e. without openings) and thus, limited research on various types of openings in SPSWs or shear panels has been performed.

Roberts and Sabouri-Ghomi [14] conducted a series of quasi-static cyclic loading tests on unstiffened steel plate shear panels with centrally placed circular openings. Based on the test results, the researchers recommended that the strength and stiffness of a perforated panel can be conservatively approximated by applying a linear reduction factor to the strength and stiffness of a similar solid panel. Deylami and Daftari [15] analyzed more than 50 models with a rectangular opening in the center of the panel using finite element method to investigate the effects of some important geometric parameters, such as plate thickness, the opening height to width ratio, and the areal percentage of the opening. The opening had only two stiffeners with limited length on its vertical edges which were not continued across the height of the panel. They concluded that the introduction of the opening, even at relatively small percentage, caused an important decrease of shear capacity. In thinner steel plate shear

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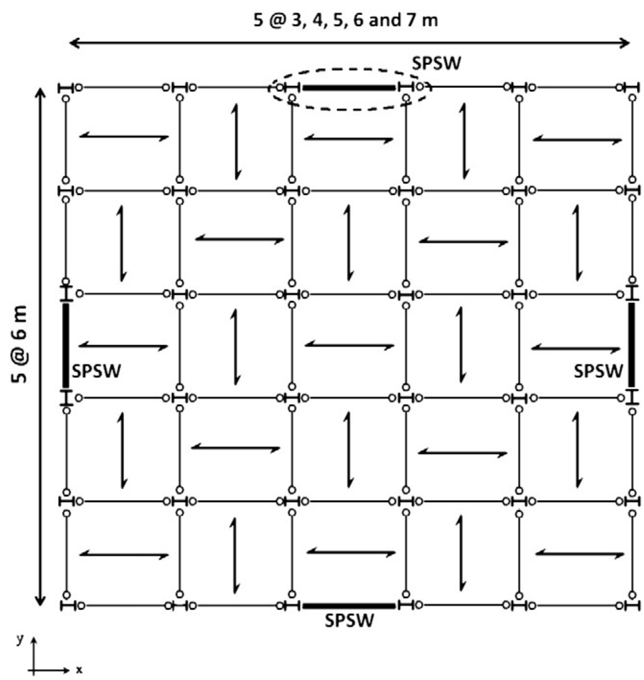


**Fig. 1.** Typical plan and considered SPSW.

walls, the maximum shear capacity has been achieved by a smaller ratio of height to width of the opening. Also, the decrease in shear capacity after reaching a maximum amount has been slower in thick plates than in thin plates. Hitaka and Matsui [16] experimentally studied the behavior of 42 one-third scale steel shear wall specimens with vertical slits under static monotonic and cyclic lateral loading. The test data indicated that, when properly detailed and fabricated to avoid premature failure due to tearing or out-of-plane buckling, the wall panels responded in a ductile manner. Vian [17] conducted experimental works on a pattern of multiple regularly spaced circular perforations in the infill plate and a reinforced quarter-circle cut-outs in the upper corners of the infill plate, and Purba [18] proposed an equation to determine the shear strength of a perforated infill plate with the specific perforation pattern proposed by Vian [17]. Alinia et al. [19–21] performed a series of finite element analyses to investigate the influence of central and near border cracks on buckling and post-buckling behavior of shear panels. It is implied from the results of this research that, anyhow, discontinuity in tension zones can have significant influence on buckling and post-buckling behavior of shear panels. The ultimate strength of perforated steel plates under shear loading was studied by Paik [22], and the linear and nonlinear behavior of steel shear panels with circular and rectangular holes by Pellegrino et al. [23]. Valizadeh et al. [24] experimentally investigated cyclic behavior of perforated steel plate shear walls with a circular opening at the center of the panel. The obtained results showed that the creation of openings reduced the initial stiffness and strength and noticeably decreased the energy absorption of the system.

Openings are often required in SPSWs for functional reasons. One of the most usual types is the large rectangular openings utilized as doors or windows to allow entry to stairs and elevators or provide outside view and light, respectively. These happen frequently when SPSWs are used in the building cores or as the facade panels. The design procedure is similar to the typical design of SPSW. In the case of such large openings, use of horizontal and vertical local boundary elements (LBE) around the opening to anchor and transmit the infill plate tension forces to the surrounding boundary members (i.e. HBE and VBE) at their ends is inevitable. Moreover, to compensate the infill plate total area reduction at the opening level, the thickness of infill panels on either side of the opening must be increased. As such, where the resulted panels are often of slender proportions, providing the same total area of the original infill will thus be adequate. However, infill plates immediately above and below the opening are the same thickness as would be provided if there were no opening. The introduction of openings and LBE does not require redesign of VBE in SPSW, especially where the openings are not repeated at every level, and the VBE size will be in turn dictated by the demands at other levels. HBE above and below the opening must be redesigned, however, due to the local overturning demands at the opening. General treatment of the design of stiffened rectangular openings in SPSWs was provided by AISC Design Guide 20 [1].

According to the author's knowledge and the literature review, there is no specific work available for explaining various aspects of the nonlinear behavior of SPSWs with stiffened large rectangular openings, and the amount and quality of changes in the system behavior due to the introduction of such openings have never been studied.

In the present study, a number of SPSW models with and without openings are numerically analyzed using the finite element method. Primary concern is paid to window-type openings. The effect of opening type, however, is considered separately by comparing the behavior of typical single-storey SPSWs with window and door-type

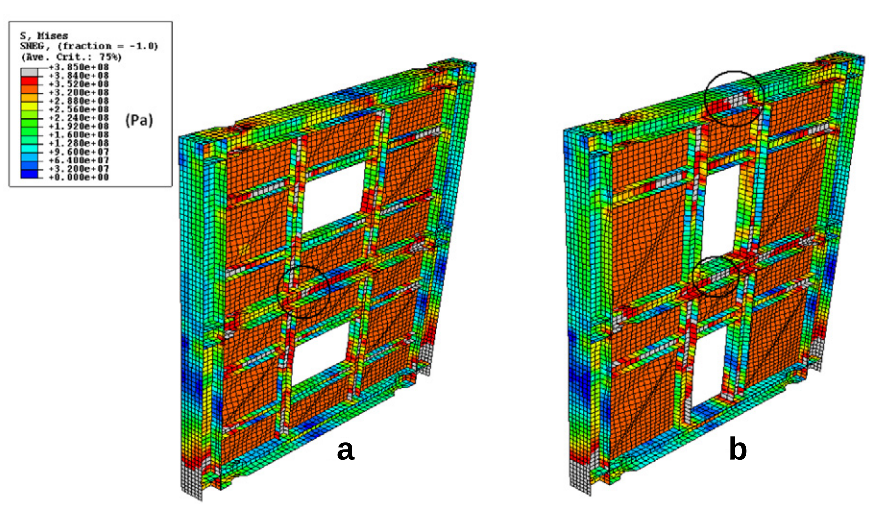


**Fig. 2.** Shear yielding occurrence in the central part of some beam webs in preliminary SPSW models with openings designed according to AISC 820: (a) a two-storey SPSW with window-type openings, and (b) a two-storey SPSW with door-type openings.

openings. Characteristics of the system behavior are discussed by comparing general behavior of typical SPSWs with and without the openings as well as by studying infill/frame behaviors of typical single-storey SPSWs with and without the opening. The effects of opening features are included by varying the geometry and horizontal location of the opening in the infill plate of typical single-storey SPSWs. The changes in the system behavior due to the introduction of the openings in terms of ultimate shear strength, ductility and stiffness are investigated over a series of SPSWs with different aspect ratios and number of stories. The changes in the behavior of the system due to the introduction of the openings at arbitrary level(s) of a four-storey SPSW, where it is not demanded to repeat the openings at every level are also considered.

## 2. Method of the study

### 2.1. Models

In this research, a variety of single and multi-storey SPSW models with different aspect ratios and opening features are considered. Fig. 1 shows the typical floor plan and the considered SPSW. Buildings of one, two, three, four, six and eight stories with a constant inter-storey height (h) of 3.5 m, measured from center to center of HBEs, are considered for this plan area. The perimeter frames assumed to have pinned beam to column connections, and that they are not incorporated in design and analysis. According to the plan in Fig. 1, gravity loads are assumed not carried by HBEs of the considered SPSW and transmitted by transverse beams to beam–column connections. SPSWs are designed according to the recommendations given in AISC Seismic Provisions [25] and AISC Design Guide 20 [1]. Besides, in design of HBEs at the opening level, the effect of the additional shear force demand resulted from reaction forces of vertical LBE and not considered in the AISC Design Guide 20 rules for design of HBEs, is also considered. Neglecting this effect was followed by an undesirable shear yielding in beam webs of some preliminary SPSW models designed per AISC 820 [1] (see Fig. 2).

The beam–column connection details include reduced beam section (RBS) at each end to ensure inelastic beam action at the desired locations as well as to limit the bending moment demand to VBEs. By utilizing RBS, the safety of beam–column connection is guaranteed and the "weak beam–strong column" criterion is taken into account. The RBS dimensions in each case are chosen in accordance with AISC 358-05 [26]. Fixed end connections are considered for all LBE. During the design, a dead load of 4.6 kPa and a live load of 2.4 kPa are used for each floor, and a dead load of 3.2 kPa and a live load of 0.96 kPa are considered for the roof. Bay width (L) of SPSW, measured from center to center of VBEs, is assumed to vary from 3 to 7 m (i.e. $L/h = 0.86$, 1.14, 1.43, 1.71 and 2). Considering the practical range of rectangular opening geometries in buildings, the lengths ($L'$) and heights ($h'$) of window-type openings are assumed to vary between $L' = 0.9$ m to $L' = 1.8$ m and $h' = 0.9$ m to $h' = 1.5$ m, respectively. Likewise, in the case of door-type openings, three different lengths of $L' = 1.0$, 1.3, 1.6 m and a constant height of $h' = 2.1$ m are selected. Window and door-type openings are assumed to introduce, respectively, at the center of infill plates and mid-span areas near the HBE below, as their default locations. Fig. 3 shows three typical single-storey SPSWs without the opening and with window and door-type openings. Based on these figures, a door-type opening may consider as a particular window-type opening, where panels 6, 7 and 8 do not exist, and panels 4 and 5 extended to the HBE below.

It should be mentioned that, in design, the minimum practical infill plate thickness ($t_w$) required for handling and welding considerations is considered to be 3.18 mm (1/8 in). The details of different SPSW models without and with openings are respectively given in Tables 1 and 2. Also, Table 3 presents the RBS connection dimensions for different HBE profiles per AISC 358-05 [26].

### 2.2. Mechanical properties of materials

The ASTM-A36 and ASTM-A572 conventional structural steel standards are, respectively, selected for infill wall and frame member (i.e. VBE, HBE and LBE) materials. The respective stress–strain diagrams that define the constitutive behaviors of the two steel materials with $E = 200$ GPa and $\upsilon = 0.3$, as depicted in Fig. 4, are selected and incorporated in the finite element models. Based on these figures, the lower yield strengths for the infill plates (327.6 MPa) in comparison to the yield strengths of frame members (385 MPa) allow yielding in the infill plates first. The Von Mises yield theory, which is known to be the most suitable one for mild steel, is used for the material yield criterion. For all incremental pushover analyses, a nonlinear isotropic hardening model which is adequate for this type of analysis is used.

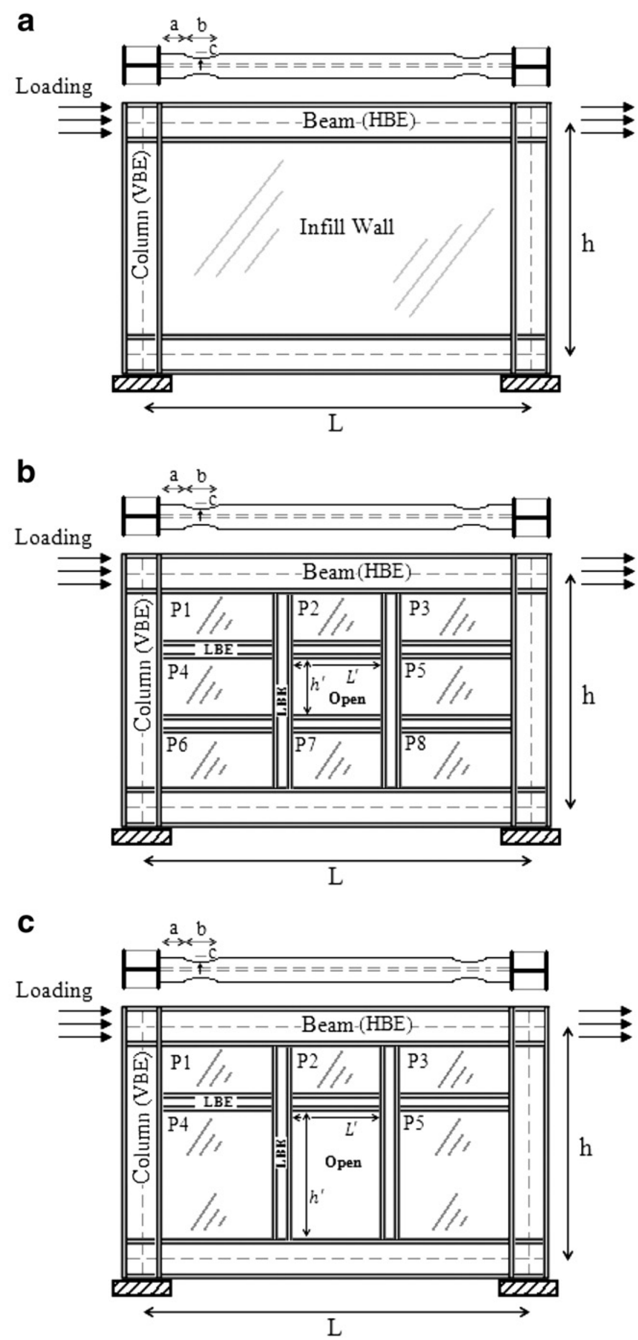


**Fig. 3.** Typical single-storey SPSW systems (a) without the opening, (b) with window-type opening and (c) with door-type opening.

**Table 1**
Infill plate thicknesses and frame member sizes at different stories of original SPSWs without the openings.

| Name | # of stories, n | Bay width, L (m) | Aspect ratio, L/h | Plate thickness, $t_w$ (mm) | HBE size | | VBE size |
|---|---|---|---|---|---|---|---|
| | | | | | Intermediate | Base and top | |
| 1S3L | 1 | 3 | 0.86 | 1st: 3.18 | – | W14×176 | W14×283 |
| 1S4L | 1 | 4 | 1.14 | 1st: 3.18 | – | W14×193 | W14×311 |
| 1S5L | 1 | 5 | 1.43 | 1st: 3.18 | – | W14×233 | W14×370 |
| 1S6L | 1 | 6 | 1.71 | 1st: 3.18 | – | W24×250 | W14×455 |
| 1S7L | 1 | 7 | 2.00 | 1st: 3.18 | – | W24×370 | W14×550 |
| 2S5L | 2 | 5 | 1.43 | 1st, 2nd: 3.18 | W14×132 | W14×233 | W14×370 |
| 3S5L | 3 | 5 | 1.43 | 1st–3rd: 3.18 | W14×132 | W14×233 | W14×370 |
| 4S3L | 4 | 3 | 0.86 | 1st–4th: 3.18 | W14×132 | W14×176 | W14×283 |
| 4S4L | 4 | 4 | 1.14 | 1st–4th: 3.18 | W14×132 | W14×193 | W14×311 |
| 4S5L | 4 | 5 | 1.43 | 1st–4th: 3.18 | W14×132 | W14×233 | W14×370 |
| 4S6L | 4 | 6 | 1.71 | 1st–4th: 3.18 | W14×132 | W24×250 | W14×455 |
| 4S7L | 4 | 7 | 2.00 | 1st–4th: 3.18 | W14×132 | W24×370 | W14×550 |
| 6S5L | 6 | 5 | 1.43 | 1st–4th: 4.76<br>5th, 6th: 3.18 | W14×132 | W14×233 | 1st–4th: W14×500<br>5th, 6th: W14×370 |
| 8S5L | 8 | 5 | 1.43 | 1st–4th: 6.35<br>5th, 6th: 4.76<br>7th, 8th: 3.18 | W14×132 | W14×233 | 1st–4th: W14×730<br>5th–8th: W14×398 |

### 2.3. Numerical modeling and method of analysis

The commercially available finite element program ABAQUS/Standard [27] is utilized for all Eigen-value and incremental nonlinear pushover analyses. All frame members and infill plates are finely meshed and modeled using a general-purpose four-node doubly-curved shell element with reduced integration (ABAQUS element S4R). Reduced integration elements are used as they give accurate results and significantly reduce running time. The geometric nonlinearity phenomenon is included as a result of large displacements with small strains.

The infill plates are considered to be connected directly to the frame members. To simulate the fix support conditions at the column bases, the bottom nodes of both columns flanges and webs are restrained from displacement in all directions. In order to replicate the effects of the concrete slab of the floors, all beam webs are also restrained against movement in the out-of-plane direction.

**Table 2**
Infill plate thicknesses and frame member sizes at different stories of SPSWs with the openings.

| Name | Original SPSW[a] | Opening type and geometry | | Stories with the openings | Infill thicknesses in different panels | | LBE size[b] |
|---|---|---|---|---|---|---|---|
| | | Type | Length × height, L′ × h′ ($m^2$) | | P1–P3, P6–P8 (if any) $t_w$ (mm) | P4, P5$t'_w$ (mm) | |
| 1S5L-W1 | 1S5L | Window | 0.9×1.2 | – | 3.18 | 6.35 | W8×67 |
| 1S3L-W2 | 1S3L | Window | 1.2×1.2 | – | 3.18 | 4.76 | W8×48 |
| 1S4L-W2 | 1S4L | Window | 1.2×1.2 | – | 3.18 | 4.76 | W8×48 |
| 1S5L-W2 | 1S5L | Window | 1.2×1.2 | – | 3.18 | 4.76 | W8×48 |
| 1S6L-W2 | 1S6L | Window | 1.2×1.2 | – | 3.18 | 4.76 | W8×48 |
| 1S7L-W2 | 1S7L | Window | 1.2×1.2 | – | 3.18 | 3.42 | W8×48 |
| 1S5L-W3 | 1S5L | Window | 1.5×1.2 | – | 3.18 | 4.76 | W8×48 |
| 1S5L-W4 | 1S5L | Window | 1.8×1.2 | – | 3.18 | 6.35 | W8×67 |
| 1S5L-W5 | 1S5L | Window | 1.2×0.9 | – | 3.18 | 4.76 | W8×48 |
| 1S5L-W6 | 1S5L | Window | 1.2×1.5 | – | 3.18 | 4.76 | W8×48 |
| 1S5L-D1 | 1S5L | Door | 1.0×2.1 | – | 3.18 | 4.76 | W10×77 |
| 1S5L-D2 | 1S5L | Door | 1.3×2.1 | – | 3.18 | 4.76 | W10×77 |
| 1S5L-D3 | 1S5L | Door | 1.6×2.1 | – | 3.18 | 4.76 | W10×77 |
| 2S5L-W3 | 2S5L | Window | 1.5×1.2 | All | 3.18 | 1st, 2nd: 4.76 | W8×48 |
| 3S5L-W3 | 3S5L | Window | 1.5×1.2 | All | 3.18 | 1st–3rd: 4.76 | W8×48 |
| 4S3L-W2 | 4S3L | Window | 1.2×1.2 | All | 3.18 | 1st–4th: 4.76 | W8×48 |
| 4S4L-W2 | 4S4L | Window | 1.2×1.2 | All | 3.18 | 1st–4th: 4.76 | W8×48 |
| 4S5L-W2 | 4S5L | Window | 1.2×1.2 | All | 3.18 | 1st–4th: 4.76 | W8×48 |
| 4S5L-W3 | 4S5L | Window | 1.5×1.2 | All | 3.18 | 1st–4th: 4.76 | W8×48 |
| 4S5L-W3(1) | 4S5L | Window | 1.5×1.2 | 1st | 3.18 | 1st: 4.76 | W8×48 |
| 4S5L-W3(2) | 4S5L | Window | 1.5×1.2 | 2nd | 3.18 | 2nd: 4.76 | W8×48 |
| 4S5L-W3(3) | 4S5L | Window | 1.5×1.2 | 3rd | 3.18 | 3rd: 4.76 | W8×48 |
| 4S5L-W3(4) | 4S5L | Window | 1.5×1.2 | 4th | 3.18 | 4th: 4.76 | W8×48 |
| 4S5L-W3(3,4) | 4S5L | Window | 1.5×1.2 | 3rd, 4th | 3.18 | 3rd, 4th: 4.76 | W8×48 |
| 4S5L-W3(2,3,4) | 4S5L | Window | 1.5×1.2 | 2nd, 3rd, 4th | 3.18 | 2nd, 3rd, 4th: 4.76 | W8×48 |
| 4S6L-W2 | 4S6L | Window | 1.2×1.2 | All | 3.18 | 1st–4th: 4.76 | W8×48 |
| 4S7L-W2 | 4S7L | Window | 1.2×1.2 | All | 3.18 | 1st–4th: 3.42 | W8×48 |
| 6S5L-W3 | 6S5L | Window | 1.5×1.2 | All | 1st–4th: 4.76<br>5th, 6th: 3.18 | 1st–4th: 7.94<br>5th, 6th: 4.76 | W10×88 |
| 8S5L-W3 | 8S5L | Window | 1.5×1.2 | All | 1st–4th: 6.35<br>5th, 6th: 4.76<br>7th, 8th: 3.18 | 1st–4th: 9.53<br>5th, 6th: 7.94<br>7th, 8th: 4.76 | W10×88 |

[a] The sizes of VBEs and HBEs and the geometry of frames in SPSWs with openings are similar to the corresponding original SPSWs without openings.
[b] For simplicity, only one section for horizontal and vertical LBE at opening levels for each case is selected.

**Table 3**
RBS connection dimensions for different HBE profiles per AISC 358-05.

| RBS dimensions | W14×132 | W14×176 | W14×193 | W14×233 | W24×250 | W24×370 |
|---|---|---|---|---|---|---|
| a (mm) | 200 | 200 | 200 | 220 | 200 | 175 |
| b (mm) | 300 | 300 | 300 | 330 | 550 | 600 |
| c (mm) | 90 | 95 | 95 | 100 | 80 | 85 |

An Initial imperfection pattern corresponding to the first buckling mode of each infill plate is applied in the model to help initiate buckling in the infill plates and development of the tension fields. Values of 0.5 and 3 mm are selected for the peak magnitude of initial imperfections in the infill plates at levels with and without the openings, respectively. Considering these imperfection values are within the limit developed by Behbahanifard et al. [28] and therefore, have no considerable influence on the analyses results. In addition, preliminary analyses verified the sufficiency of the considered values. Lateral loads, as shown in Fig. 3, are applied to the exterior nodes of panel zones on either side of each storey beam and are gradually increased from zero to a magnitude beyond the system's capacity. The ultimate displacement limit is considered to occur at a drift ratio of 2.5% at least at one of the stories of SPSWs per ASCE 7-05 [29].

### 2.4. Validation and verification of results

Finite element modeling, boundary conditions and loading procedures were validated by comparing published test results with the corresponding analysis results. A four-storey specimen tested by Driver et al. [7] and a single-storey specimen (only SPSW2 specimen) tested by Lubell et al. [10] were modeled using the finite element program. The material properties reported by the original researchers were used in Pushover analyses of finite element models. Fig. 5(a) and (b) compares the current FE pushover curves to the envelopes of the test specimen hysteresis curves. It is inferred that the used analytical method has been successful to estimate the actual behavior of the SPSW systems in comparison with the experimental results with good approximate precision. Fig. 5(c) and (d) depicts the corresponding Mises stress distributions in the FE models at the ultimate state. As shown, local buckling in the column flanges below the first storey of Driver's specimen FE model and significant inward bending deformations in the columns of Lubell's specimen FE model have taken place.

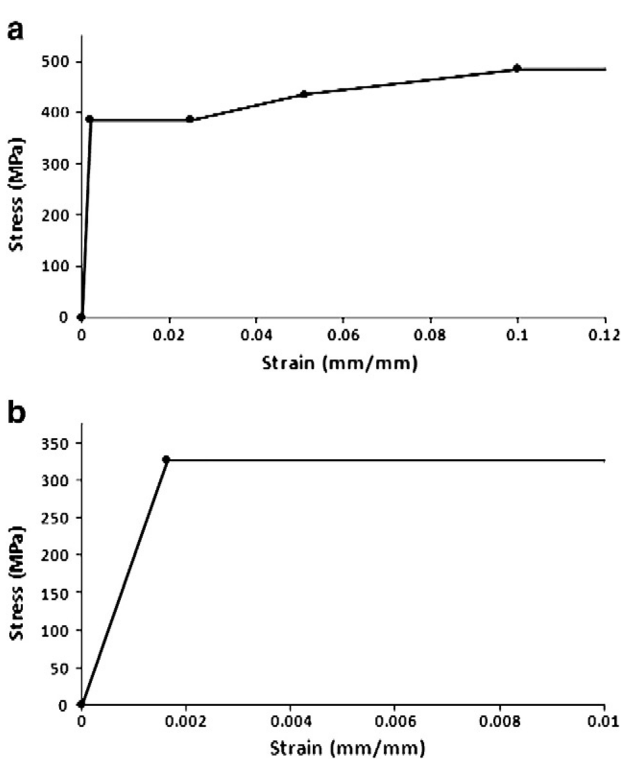


**Fig. 4.** Materials stress–strain curves, adopted from Ref. [2]: (a) frame members (VBEs, HBEs and LBE), and (b) infill plates.

## 3. Discussion of results

### 3.1. General behavior

Figs. 6 and 7 show general “lateral load–displacement” and “stiffness–drift ratio” curves of typical SPSW systems with and without the opening. Based on recent research [2], the general behavior of SPSWs can be outlined by three stages. As such, the general behavior of a SPSW with the opening is described and compared to the corresponding SPSW without the opening by dividing these curves into three parts as follows:

1- (OA). At very low lateral loads, the whole of both the systems with and without the opening behaves elastically. At the center of the infill plates, away from boundary elements, the plates are subject to essentially pure shear, with equal principal tensile and compressive stresses oriented at a 45° angle to the direction of load. With the increase of load, where the plates in both the systems are of slender proportions, they buckle simultaneously in compression. As a result, the system without the opening experiences a big loss of stiffness, while stiffness of the system with the opening does not change significantly. As buckling occurs, the load-resisting mechanism changes from in-plane shear to an inclined tension field and Postbuckling deformations continue until first yielding occurs in the infill plates (point A in Figs. 6 and 7). During this stage, the difference between the pushover curves of the two systems is negligible, although the stiffness of the system with the opening is relatively higher than that of its corresponding system without the opening. Similarly, frames in both the systems remain essentially elastic and their stress levels are very low. Fig. 8 depicts the Mises stress distribution of typical single-storey SPSW systems with and without window and door openings at a load magnitude corresponding to point A. As shown in the figures, first yielding does not necessarily occur in all the infill plates of the systems with the openings, simultaneously.

2- (AC). In the second stage, the infill plates in two systems with and without the opening behave both materially and geometrically nonlinear, while frame members still remain elastic. Yield zones distribute within the infill plates of the two systems. However, the distribution in each infill plate panel of the system with the opening occurs separately. Stiffness of the system with the opening decreases with an almost similar slope as the previous stage, while stiffness of the system without the opening is almost constant until the formation of yield zones (point B), followed by a noticeable fall. Anyway, stiffness of the system with the opening is mainly higher than that of the system without the opening up to point C which is corresponding to the first yield occurrence in frame members. Similarly, both the systems lose a considerable portion of their stiffness due to significant yielding of the infill plates (except in corner regions) and the pushover curves of the two systems start to diverge, although the difference between curves is not yet significant. Fig. 9 shows the Mises stress distribution

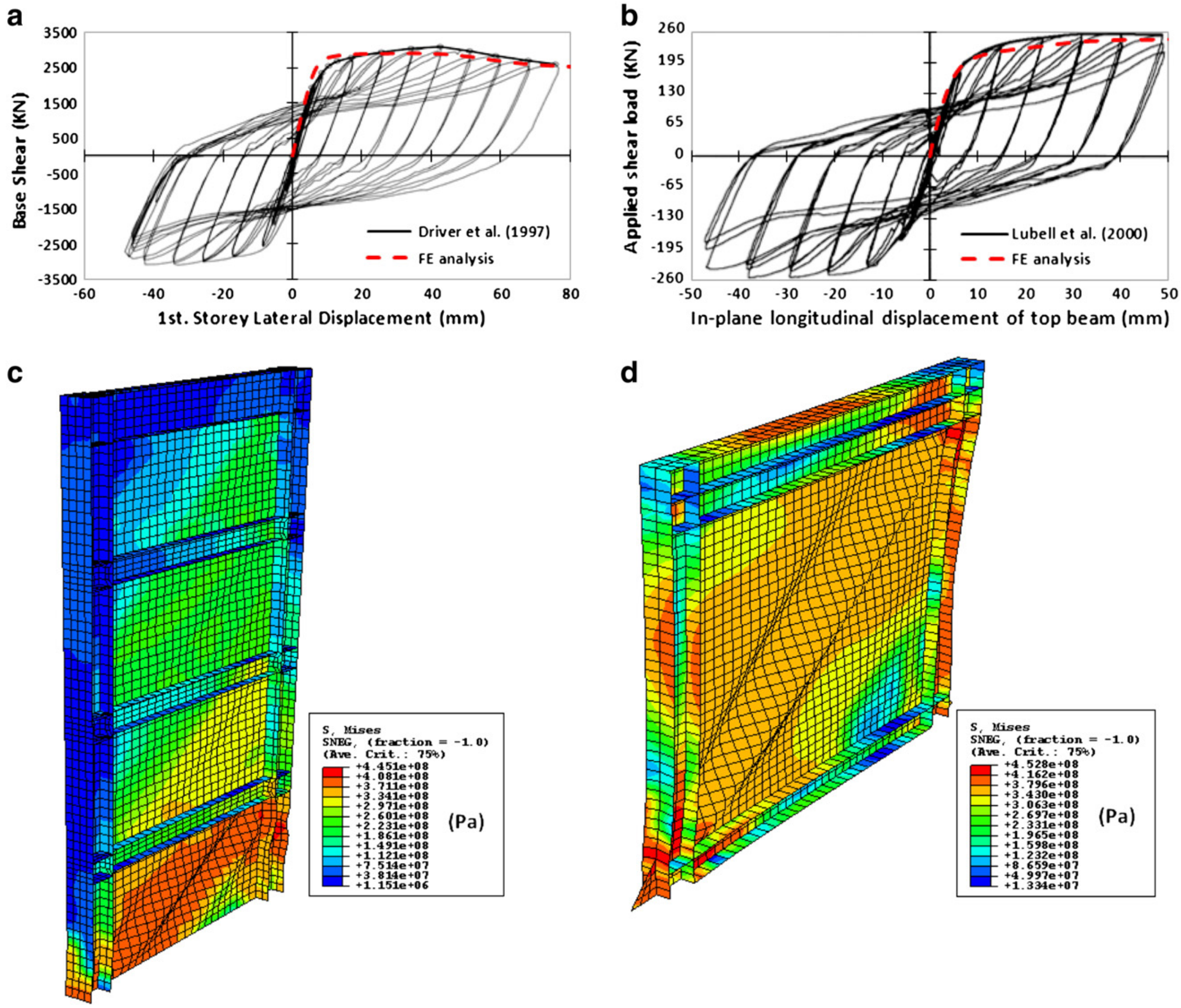


**Fig. 5.** Validation of FE model: (a) comparison of pushover analysis with test results of Driver et al. [7], (b) comparison of pushover analysis with test results of Lubell et al. [10], (c) Mises stress of FE model of Driver's specimen at the ultimate state, and (d) Mises stress of FE model of Lubell's specimen (SPSW2) at the ultimate state.

of typical single-storey SPSWs with and without window and door openings at a load magnitude corresponding to point C. As shown in the figures, first yielding in frame members in the systems with the openings, unlike to the system without the opening, typically happens in LBE rather than HBE.

3- (CD). During the third stage, in both the systems, frames behave materially nonlinear and the entire infill plates even in corner regions have fully yielded. Partial or complete plastic hinges form in frame members and at last, the systems reach their full strength at point D. In this stage, stiffness of the system with the opening is slightly higher than that of the corresponding system without the opening and therefore, the difference between the pushover curves of the two systems is partially increased. Eventually, a relatively higher strength is observed for the system with the opening compared to the system without the opening, at the ultimate state. The Mises stress distribution of typical single-storey SPSWs with and without window and door openings at the ultimate state is shown in

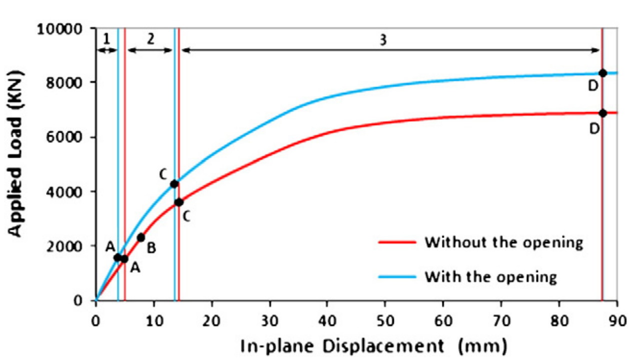


**Fig. 6.** Typical lateral load–displacement curves of SPSWs with and without the opening.

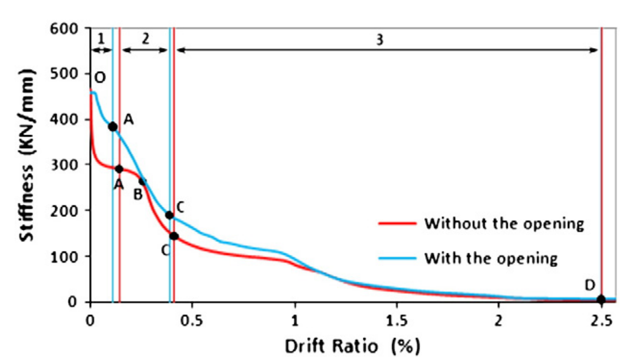


**Fig. 7.** Typical stiffness–displacement curves of SPSWs with and without the opening.

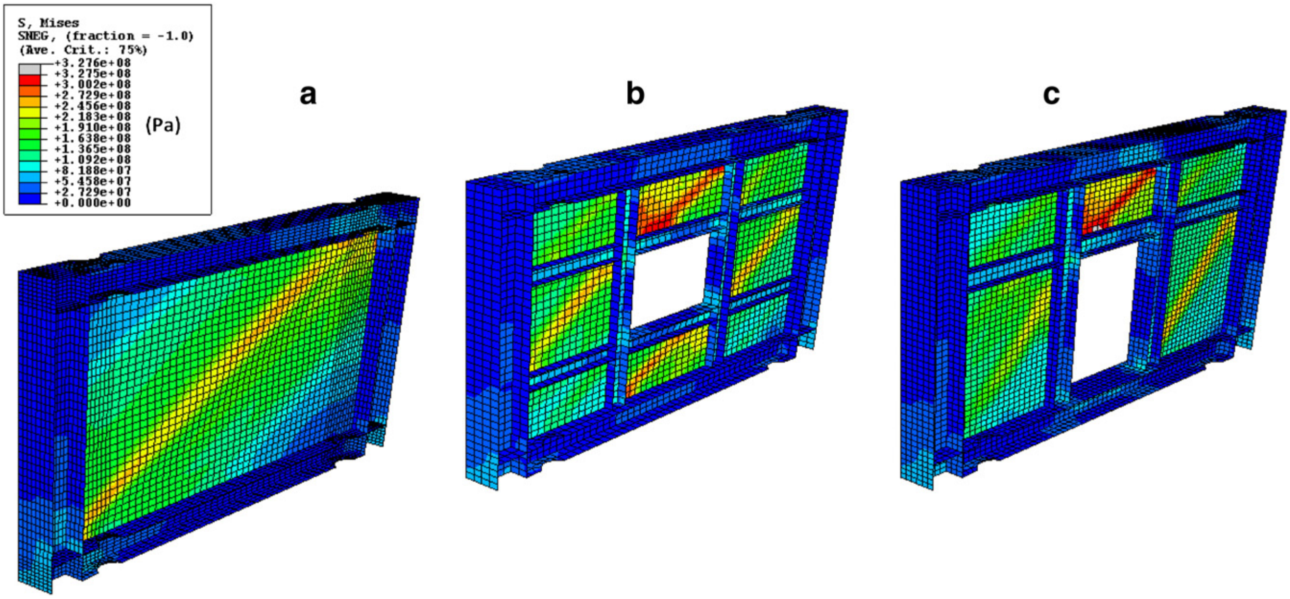


**Fig. 8.** Mises stress distributions in single-storey SPSWs with and without the openings at point A: (a) SPSW 1S5L, (b) SPSW 1S5L-W3 with a window opening, and (c) SPSW 1S5L-D2 with a door opening.

Fig. 10, where yield zones have spread across all infill plates and plastic hinges have occurred in frame members.

### 3.2. Infill-frame behavior characteristics

An effective method to evaluate the behavior of infill plates in SPSWs with and without openings is to measure and to compare the amounts of absorbed shear storey. Fig. 11 compares the amount of shear forces carried by the infill plates at three different levels (below the opening level (1), at the opening level (2) and above the opening level (3)) of a typical single-storey SPSW with window opening (1S5L-W3) to that of its corresponding SPSW without the opening (1S5L) at lower level at different drift ratios. The absorbed shear forces in each level are calculated by means of integrating shear stresses across the width of infill plates at that level. Fig. 12, on the other hand, shows the percentage contribution shares of the infill plates of the considered systems with and without the opening at different drift ratios.

Fig. 11 illustrates that infill plates in the SPSWs with and without the opening behave in a different manner, although their ultimate strengths are almost the same. As shown in the figure, infill plates in the system with the opening reach their full tension strength at around the drift ratio of 1% which is lower than the drift ratio of 1.5%, where the infill plate in the system without the opening reaches

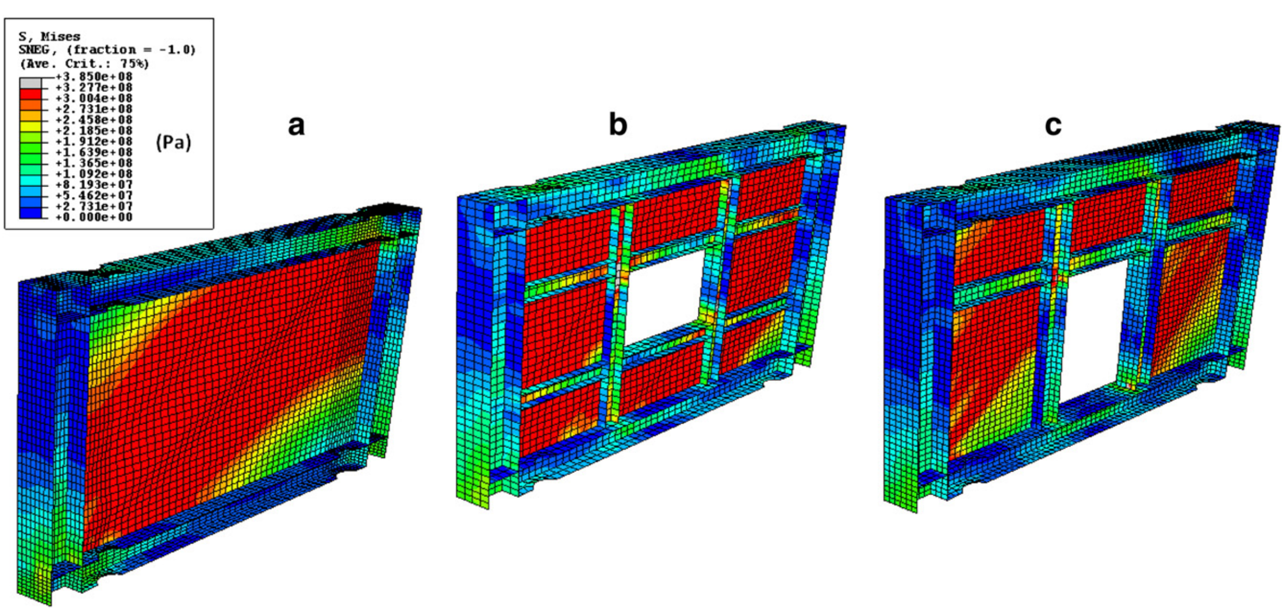


**Fig. 9.** Mises stress distributions in single-storey SPSWs with and without the openings at point C: (a) SPSW 1S5L, (b) SPSW 1S5L-W3 with a window opening, and (c) SPSW 1S5L-D2 with a door opening.

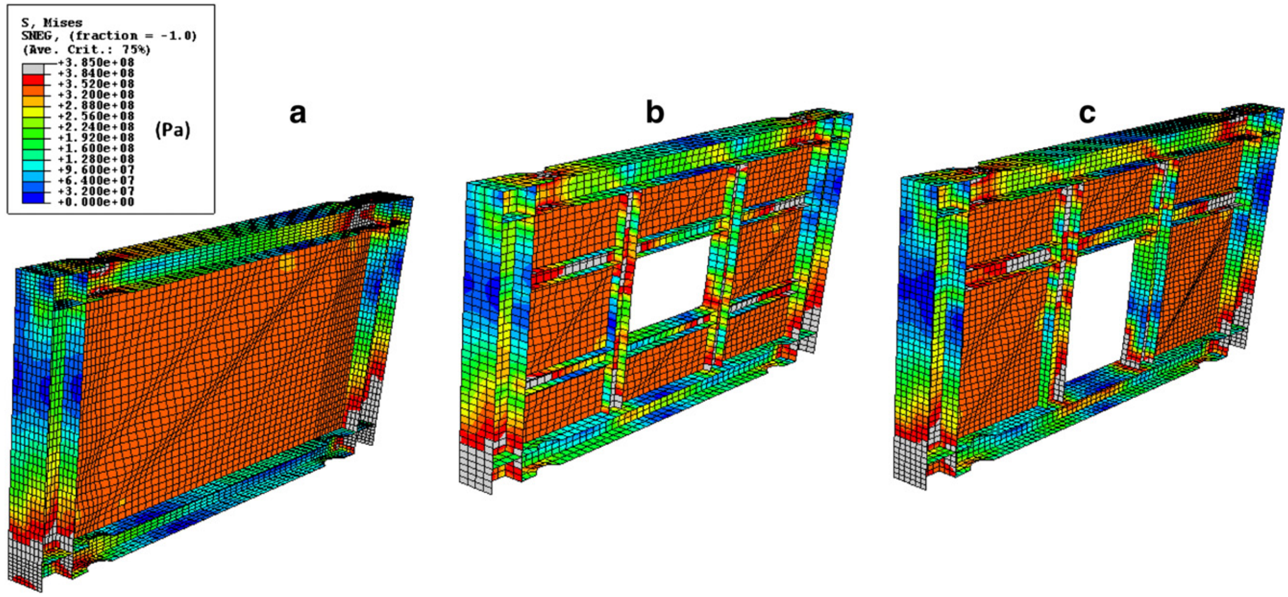


**Fig. 10.** Mises stress distributions in single-storey SPSWs with and without the openings at point D: (a) SPSW 1S5L, (b) SPSW 1S5L-W3 with a window opening, and (c) SPSW 1S5L-D2 with a door opening.

their full tension strength. Fig. 12 shows that the contribution curves from the infill plates in the two systems with and without the opening at lower level are almost similar (less than 10% deviation).

Figs. 11 and 12 also show that infill plates at different levels of the SPSW with the opening act differently. The contribution from the infill plates at upper levels is significantly higher than the lower level up to a drift ratio of around 0.1%, where the first yield occurs in the infill plates. Thereafter, the contribution curves for different levels start to converge and flatten until they become horizontal at around the drift ratio of 1%. Beyond the drift ratio of 1%, all the infill plate panels have almost fully yielded and additional loading is mainly absorbed by the frame members through flexural deformation.

Fig. 13 compares the behavior of frames in the considered systems with and without the opening at different drift ratios. The figure shows that the introduction of the opening and LBE in the system provides some additional strength and stiffness for the frame which in turn result in a relatively stronger system. Figs. 11 and 13 demonstrate that the frame and infill plates behave supplementally at different levels of the system with the opening. With the increase of the portion of storey shear resisted by the infill plates at a certain level, the portion of storey shear resisted by the frame decreases at that level and vice versa. This indicates that, generally, frames and infill plates in SPSW dual systems act as two interdependent systems and the behavior of each one relies on each other.

### 3.3. Effects of different infill plate thicknesses at the opening level

The effects of use of thicker and thinner than the required plate thickness for the infill panels on either side of the opening (panels 4, 5 in Fig. 3) are studied here. This may sometimes occur due to the lack of the required plate thicknesses on the market or miscalculation of the required plate thicknesses. Besides, this also occurs when the calculated thickness lies between the two available thicknesses.

Fig. 14 illustrates the effects of use of thinner or thicker than the required plate thickness ($t'_{w(req)} = 4.76$ mm) on either side of the opening on the ultimate strength of a typical single-storey SPSW with the opening (SPSW 1S5L-W3). Note that other than the plate thickness on either side of the opening ($t'_w$), all other properties were considered the same in the considered cases. As shown in the figure, the changes in the ultimate strengths for different plate thicknesses are given in dimensionless form. In fact, the ultimate strengths of SPSW, infill plates and frame obtained for each case were respectively divided by the corresponding strengths from the original SPSW having the required plate thickness. Fig. 14 indicates that if a thicker than the required plate thickness is selected for the plates on either side of the opening, the total shear force resisted by the infill plates at this level increases, while the shear force resisted by the frame decreases. As a result, the ultimate strength of the SPSW does not increase significantly even for the thickest plate (less than 8% for $t'_w = 9.53$ mm). Fig. 14 also shows that the total

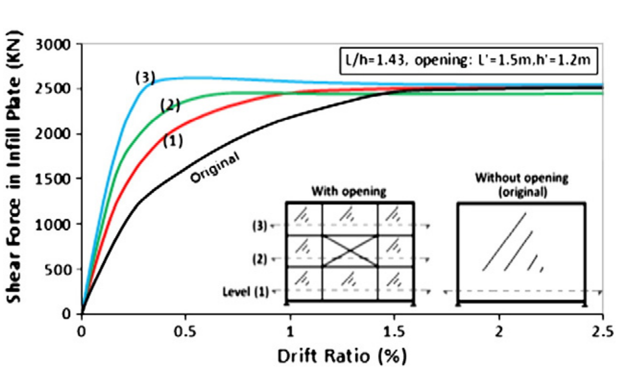


**Fig. 11.** Comparison of absorbed shear forces by the infill plates of single-storey SPSWs with and without window opening (SPSWs 1S5L-W3 and 1S5L).

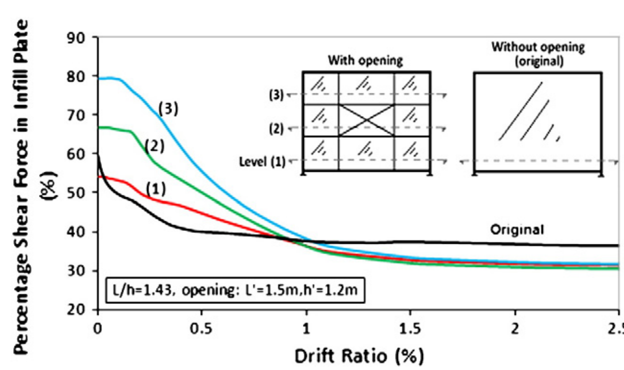


**Fig. 12.** Comparison of percentage shear forces absorbed by the infill plates of single-storey SPSWs with and without window opening (SPSWs 1S5L-W3 and 1S5L).

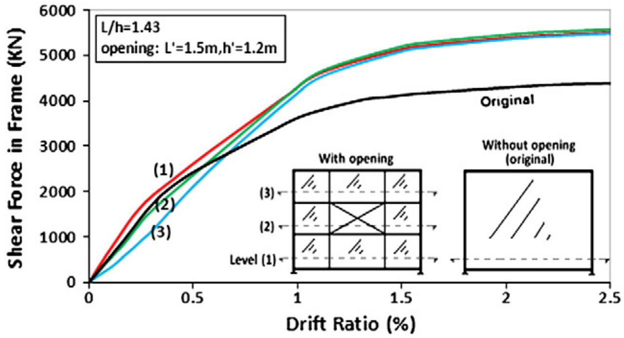


**Fig. 13.** Comparison of absorbed shear forces by the surrounding frame members of single-storey SPSWs with and without window opening (SPSWs 1S5L-W3 and 1S5L).

shear force resisted by the infill plates does not increase proportionally with the increase of the plate thickness. This is, in fact, because of the relatively lower stiffness and strength of the SPSW immediately above and below the opening and the limitation of the stiffness and strength of the LBE. Thus, the full tension strength of thicker infill plates at the opening level is not realized even at the ultimate state. Contrarily, if a thinner than the required plate thickness is selected for the plates on either side of the opening, the total shear force resisted by the infill plates at this level decreases proportionally with the decrease of the plate thickness. As a result, some additional shear forces undesirably imposed on the VBEs at this level, and the ultimate strength of the system partially decreases (about 12% for extremely thin plate $t'_w = 0$).

### 3.4. Effects of various LBE sizes

In this section, the effects of use of one section bigger (i.e. W10 × 77) and two sections smaller (i.e. W8 × 24 and W4 × 13) than required section (i.e. W8 × 48) for the LBE in a typical single-storey SPSW with the opening (SPSW 1S5L-W3) are studied. Other than the LBE sizes, all other properties were considered the same in the considered cases. Table 4 presents the infill/frame participation shares on the system ultimate strength for different LBE sizes. Shear forces absorbed by frames and infill plates are presented for the lower level of the systems. The results indicate that if a bigger than the required section is selected for the LBE, an increase in the system ultimate strength only due to the increase in the ultimate strength of the frame occurs. On the contrary, if a weaker than the required profile is selected for the LBE, a reduction in the system ultimate strength not only due to the reduction in the ultimate strength of the frame but also due to the reduction in the ultimate strength of the infill plates occurs. Indeed, the surrounding LBE around the panels due to premature yielding or excessive deformation were not capable of developing

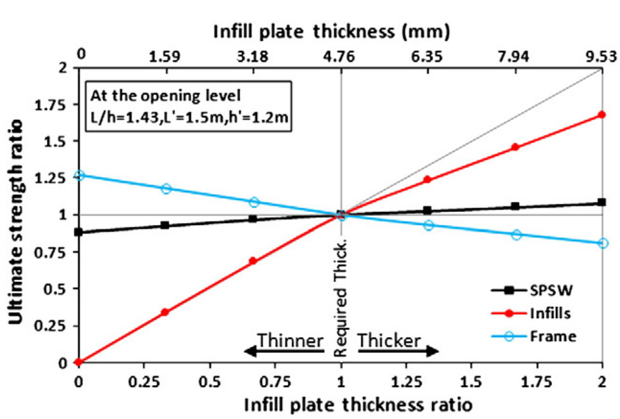


**Fig. 14.** Effect of thickness of infill plats on either side of the opening on the system strength.

**Table 4**
Infill/frame shares on the story shear at lower level of a single-storey SPSW with L/h = 1.43 and specific window opening (L′ = 1.5 m and h′ = 1.2 m) for different LBE profiles.

| LBE section | Infill (KN) | Frame (KN) | SPSW = infill + frame (KN) | Difference (KN) | | |
|---|---|---|---|---|---|---|
| | | | | Infill | Frame | SPSW |
| W10 × 77 | 2505 | 6516 | 9021 | + 3 | + 999 | + 1001 |
| W8 × 48[a] | 2502 | 5517 | 8019 | 0 | 0 | 0 |
| W8 × 24 | 2392 | 4865 | 7257 | − 110 | − 652 | − 762 |
| W4 × 13 | 2187 | 4723 | 6910 | − 315 | − 794 | − 1109 |

[a] Designed LBE section.

the full tension strength of the plates, which in turn caused a weakness in plate action and correspondingly, increased the demands on boundary frame members in an unsuitable manner.

### 3.5. Effects of the opening geometry, location and type

The effects of opening geometry and type are considered by comparing the behavior of several single-storey SPSWs with an aspect ratio of 1.43 and various window (SPSWs 1S5L-W1, 1S5L-W2, 1S5L-W3, 1S5L-W4, 1S5L-W5 and 1S5L-W6) and door-type openings (SPSWs 1S5L-D1, 1S5L-D2 and 1S5L-D3). In the case of window-type openings, different opening heights (i.e. h′ = 0.9, 1.2 and 1.5 m) and lengths (i.e. L′ = 0.9, 1.2, 1.5 and 1.8 m) and in the case of door-type openings, a constant opening height (i.e. h′ = 2.1 m) and different opening lengths (L′ = 1.0, 1.3 and 1.6 m) were considered. Except the LBE sizes and thickness of panels on either side of the openings resulted from different opening geometries, other properties were similar in all the considered cases (see Table 2). A summary of the ultimate strengths of all SPSWs with and without openings are presented in Table 5. Comparison of the results in Table 5 for the above cases indicates that the behavior of the SPSWs with stiffened openings is not affected much by the opening types and

**Table 5**
Summary of the ultimate strengths of different SPSWs with and without openings.

| SPSWs without openings | | | | SPSWs with openings | | | |
|---|---|---|---|---|---|---|---|
| Name | SPSW (KN) | Infill[a] (KN) | Frame[a] (KN) | Name | SPSW (KN) | Infill[a] (KN) | Frame[a] (KN) |
| 1S3L | 4746 | 1425 | 3321 | 1S5L-W1 | 8239 | 2510 | 5729 |
| 1S4L | 5597 | 1960 | 3637 | 1S3L-W2 | 6057 | 1482 | 4575 |
| 1S5L | 6885 | 2505 | 4380 | 1S4L-W2 | 6573 | 1950 | 4623 |
| 1S6L | 9587 | 3050 | 6537 | 1S5L-W2 | 8103 | 2498 | 5605 |
| 1S7L | 12,632 | 3544 | 9088 | 1S6L-W2 | 10,996 | 3074 | 7922 |
| 2S5L | 6602 | 2501 | 4100 | 1S7L-W2 | 13,662 | 3575 | 10,087 |
| 3S5L | 6185 | 2509 | 3676 | 1S5L-W3 | 8019 | 2517 | 5502 |
| 4S3L | 3727 | 1417 | 2310 | 1S5L-W4 | 8084 | 2489 | 5595 |
| 4S4L | 4582 | 1950 | 2632 | 1S5L-W5 | 8177 | 2527 | 5650 |
| 4S5L | 5617 | 2519 | 3098 | 1S5L-W6 | 8062 | 2502 | 5560 |
| 4S6L | 6945 | 3055 | 3890 | 1S5L-D1 | 8538 | 2600 | 5938 |
| 4S7L | 8333 | 3539 | 4763 | 1S5L-D2 | 8330 | 2408 | 5922 |
| 6S5L | 7328 | 3408 | 3920 | 1S5L-D3 | 8194 | 2267 | 5927 |
| 8S5L | 8744 | 4597 | 4147 | 2S5L-W3 | 7925 | 2519 | 5406 |
| | | | | 3S5L-W3 | 7484 | 2553 | 4931 |
| | | | | 4S3L-W2 | 4835 | 1497 | 3338 |
| | | | | 4S4L-W2 | 5694 | 2022 | 3672 |
| | | | | 4S5L-W2 | 6897 | 2577 | 4320 |
| | | | | 4S5L-W3 | 6888 | 2560 | 4328 |
| | | | | 4S5L-W3(1) | 6386 | 2623 | 3763 |
| | | | | 4S5L-W3(2) | 6145 | 2513 | 3632 |
| | | | | 4S5L-W3(3) | 5851 | 2503 | 3348 |
| | | | | 4S5L-W3(4) | 5636 | 2494 | 3142 |
| | | | | 4S5L-W3(3,4) | 5946 | 2525 | 3421 |
| | | | | 4S5L-W3(2,3,4) | 6447 | 2537 | 3910 |
| | | | | 4S6L-W2 | 8370 | 3071 | 5299 |
| | | | | 4S7L-W2 | 9571 | 3543 | 6028 |
| | | | | 6S5L-W3 | 9197 | 3586 | 5611 |
| | | | | 8S5L-W3 | 11,146 | 4965 | 6181 |

[a] Shear forces in the infill plates and frames are presented for the lower level.

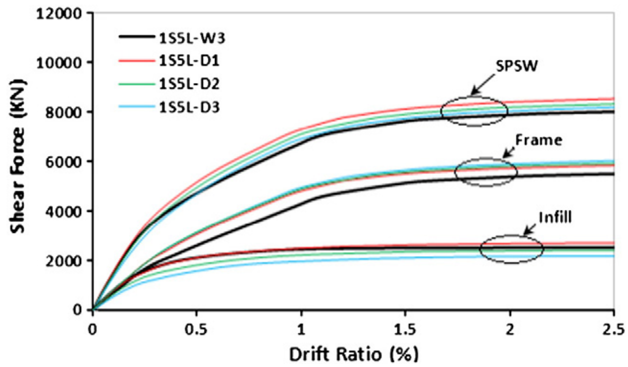


**Fig. 15.** Comparison of shear force-drift ratio curves of SPSWs with door-type (1S5L-D1, 1S5L-D2 and 1S5L-D3) and window-type (1S5L-W3) openings.

geometries, especially when the designed LBE are of similar section. In fact, the small differences between the results are mainly due to different LBE sizes. Anyway, the maximum difference between the overall strengths of the considered cases is only about 5%. Fig. 15, on the other hand, compares "shear force–drift ratio" curves of four typical single-storey SPSWs with an aspect ratio of 1.43, one with a window-type opening (SPSW 1S5L-W3) and the others with door-type openings (SPSWs 1S5L-D1, 1S5L-D2 and 1S5L-D3). The results in this figure confirm the above discussion.

Moreover, in addition to the default central location of the window opening in a typical single-storey SPSW (1S5L-W3), three different horizontal locations (i.e. near the tensile or left VBE (case Left), near the compressive or right VBE (case Right) and two half-length near both the VBEs (case Left–Right)) for the opening are considered. The Mises stress distribution of the considered cases at the ultimate state is shown in Fig. 16. Table 6 presents a summary of the ultimate strengths of the considered cases. It is apparent from the results that, as the opening type and geometry, the opening location has a very little influence on the system ultimate strength, too (about 5% difference in the overall strengths).

**Table 6**
Effect of different opening locations on the ultimate strength of a typical single-storey SPSW with L/h = 1.43.

| Opening location (case) | SPSW (KN) | Infill (KN) | Frame (KN) |
|---|---|---|---|
| Center[a] | 8019 | 2517 | 5502 |
| Left | 7721 | 2373 | 5348 |
| Right | 7625 | 2483 | 5142 |
| Left–right | 8029 | 2493 | 5536 |

[a] Default opening location.

### 3.6. Comparisons of the behavior of SPSWs with and without opening

As mentioned in Section 3.2, the introduction of openings and LBE in SPSWs provides some additional strength and stiffness for the system. In reality, the horizontal LBE in SPSWs acting as struts for VBEs stiffen the frame, to some extent, in addition to primarily allowing development of the infill plate full tension strength. As such, the VBE at the level of the opening can be redesigned considering the decreased height between the horizontal LBE for flexure due to infill plate tension. However, in most cases, this redesign need not be performed, as the required VBE section will be governed by other levels. In this section, the behavior of SPSWs with stiffened openings having different aspect ratios and number of stories is compared with that of their corresponding SPSWs without the openings in terms of strength, stiffness and ductility.

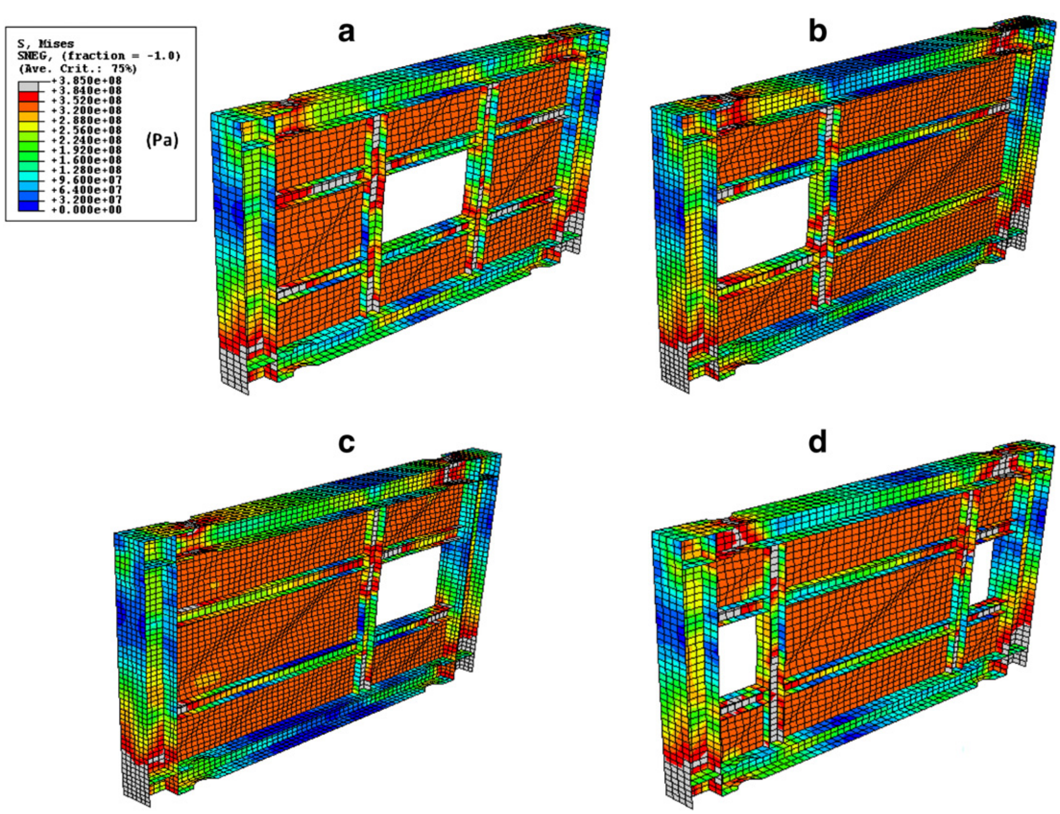


**Fig. 16.** Mises stress distributions in typical single-storey SPSWs (L/h = 1.43) with four different opening locations: (a) with the opening (L′ = 1.5 m and h′ = 1.2 m) in the center of the infill plate (case Center), (b) with the opening (L′ = 1.5 m and h′ = 1.2 m) near the tensile VBE (case Left), (c) with the opening (L′ = 1.5 m and h′ = 1.2 m) near the compressive VBE (case Right), and (d) with two half-length openings (L′ = 0.75 m and h′ = 1.2 m) near both the VBEs (case Left–Right).

*3.6.1. System strength*

*3.6.1.1. Different aspect ratios (L/h = 0.86 ~ 2).* Fig. 17 shows the variations of the ultimate strength ratios of SPSWs with one and four stories (n = 1 and 4) and specific window openings at every level (L′ = h′ = 1.2 m) to that of their corresponding SPSWs without the openings at the first storey versus aspect ratio. The results confirm that the infill plate strengths in the SPSWs of different aspect ratios with and without the openings are almost the same. The ultimate strength of the frames due to the introduction of the openings and LBE is always increased, although the ratio of the increase in the frame ultimate strength is generally decreased with the aspect ratio. As a result, the ultimate strength of the SPSWs with the openings is always higher than that of their corresponding SPSWs without the openings and the strength ratios decrease from 1.28 to 1.08 and 1.30 to 1.15, respectively, for the single and four-storey SPSWs, with the increase of the aspect ratio from 0.86 to 2.

*3.6.1.2. Different number of stories (n = 1 ~ 8).* Fig. 18 shows the variations of the ultimate strength ratios of SPSWs with an aspect ratio of 1.43 and specific window openings at every level (L′ = 1.5 m, h′ = 1.2 m) to that of their corresponding SPSWs without the openings at the first storey versus number of storey. The results show that, the ultimate strength of the infill plates due to the introduction of the openings for the SPSWs with one to four stories (n ≤ 4), as expected, is almost unchanged. However, a slight increase in the ultimate strength of the infill plates of the taller SPSWs (i.e. n = 6 and 8) is observed (up to 8%). The ultimate strength ratio of the frames increases from 1.25 for the shortest SPSW to 1.49 for the tallest SPSW. As a result, the ultimate strength ratio of the SPSWs does not increase significantly with the height of the system. Base on the results in Fig. 18, an average increase of 22% in terms of system strength due to the introduction of the openings in the SPSWs of one to eight stories and with an aspect ratio of 1.43 is observed.

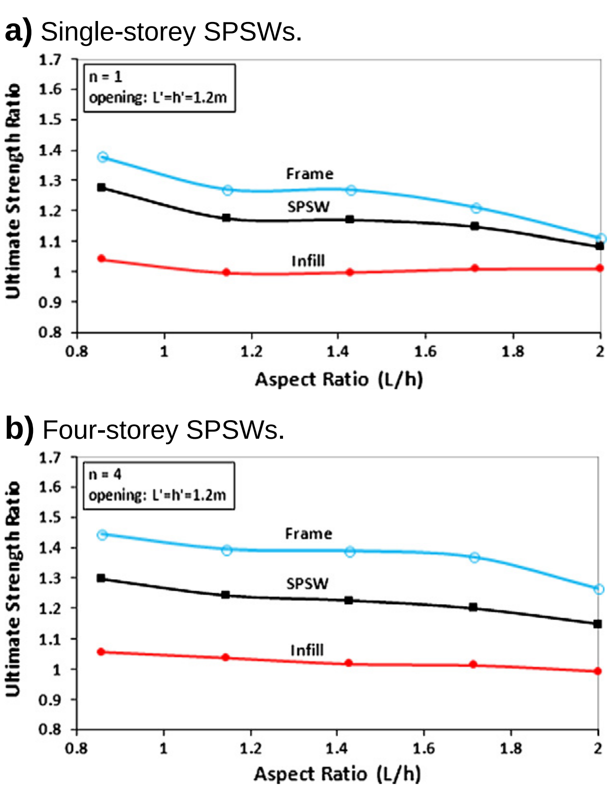


**Fig. 17.** Variations of the ultimate strength ratios of frame, infill plate and SPSW with aspect ratio for single and four-storey SPSWs with specific window opening (L′ = h′ = 1.2 m).

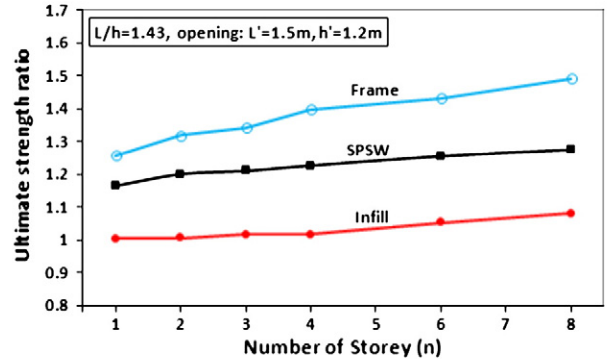


**Fig. 18.** Variations of the ultimate strength ratios of frame, infill plate and SPSW with number of storey for SPSWs with L/h = 1.43 and specific window openings at every level (L′ = 1.5 m, h′ = 1.2 m).

The situation where the openings were not required to repeat at every level and thus, introduced only at arbitrary level(s) was also examined through the analyses of eight different four-storey cases. It was assumed that all the SPSWs had an aspect ratio of 1.43, and all the openings had a similar type and geometry (window-type with L′ = 1.5 m and h′ = 1.2 m). In four cases, the openings were assumed to introduce only at one level of the system (SPSWs 4S5L-W3(1), 4S5L-W3(2), 4S5L-W3(3) and 4S5L-W3(4)), and in two cases, the openings were assumed to introduce at the upper two and at the upper three stories of the system (SPSWs 4S5L-W3(3,4) and 4S5L-W3(2,3,4), respectively). Also, two cases of without the openings (SPSW 4S5L) and with the openings at every level (SPSW 4S5L-W3) were analyzed as the lower and upper bounds, respectively, to the potential responses of all possible opening introduction patterns at stories. Fig. 19 shows "base shear–roof displacement" curves for the considered cases. As shown in the figures, the behavior of SPSWs with different patterns of opening introduction at stories depending on both the number and location of stories with the openings lies between the upper and lower bound cases. The behavior of the system is much influenced by the introduction of the opening at least at the first or second level of the system, whereas the introduction of the opening at the third or especially fourth level has a minimal effect.

*3.6.2. Stiffness and ductility*

As mentioned in Section 3.1, SPSWs without the openings due to early buckling of their infill plates at very early stages of loading (less than a drift ratio of around 0.03%) experience a significant loss of stiffness. In fact, the introduction of openings and LBE, especially in SPSWs with large openings and normal aspect ratios, separates the infill plates into the smaller subpanels which are normally of slender proportions, behave almost separately and have slenderness

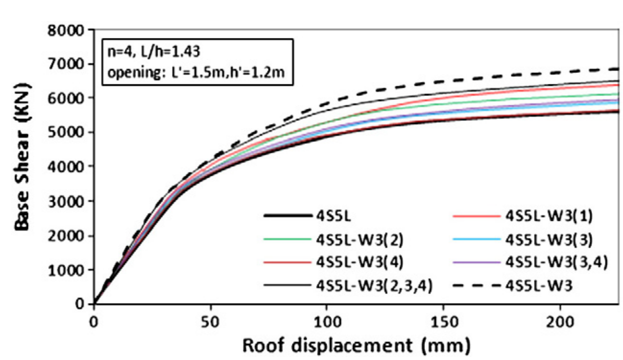


**Fig. 19.** Comparison of base shear-roof displacement curves of four-storey SPSWs with L/h = 1.43 for different opening introduction patterns at arbitrary level(s) for window openings of L′ = 1.5 m and h′ = 1.2 m.

**Table 7**
Effects of the introduction of the openings on the stiffness and ductility of SPSWs with one and four stories and different aspect ratios.

| Aspect ratio, L/h | n = 1 | | | | | n = 4 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Model name | $K'$ (KN/mm) | $\mu'$ | Ratio | | Model name | $K'$ (KN/mm) | $\mu'$ | Ratio | |
| | | | | $\frac{K'}{K}$ | $\frac{\mu'}{\mu}$ | | | | $\frac{K'}{K}$ | $\frac{\mu'}{\mu}$ |
| 0.86 | 1S3L-W2 | 309.1 | 5.06 | 1.46 | 0.81 | 4S3L-W2 | 56.6 | 3.35 | 1.23 | 0.79 |
| 1.14 | 1S4L-W2 | 380.1 | 5.82 | 1.46 | 0.85 | 4S4L-W2 | 86.9 | 4.04 | 1.27 | 0.79 |
| 1.43 | 1S5L-W2 | 493.1 | 6.14 | 1.54 | 0.88 | 4S5L-W2 | 125.2 | 4.79 | 1.35 | 0.82 |
| 1.72 | 1S6L-W2 | 630.0 | 5.99 | 1.55 | 0.93 | 4S6L-W2 | 165.2 | 5.34 | 1.37 | 0.84 |
| 2.00 | 1S7L-W2 | 744.1 | 5.55 | 1.56 | 0.92 | 4S7L-W2 | 195.9 | 5.38 | 1.38 | 0.83 |

ratios considerably lower than that of the original infill plates without openings. These characteristics help the system stiffness to be well preserved after buckling occurs in the infill plates at the early stages of loading. In typical thin SPSWs, buckling of the infill plates due to gravity or fabrication tolerances occurs even before the application of lateral loads. Therefore, an effective estimate of the system stiffness is found by considering the effect of early buckling of infill plates on the stiffness of the system.

Tables 7 and 8 compare the stiffness (K′) and ductility ratio (μ′) of SPSWs with the openings and with different aspect ratios and heights to the stiffness (K) and ductility ratio (μ) of their corresponding SPSWs without the openings. The results in Table 7 are presented for SPSWs of one and four stories and with different aspect ratios ranged between L/h = 0.86 and L/h = 2 and the results in Table 8 are presented for SPSWs with an aspect ratio of 1.43 and different number of stories ranged from one to eight. In calculation of the system stiffness, loss of stiffness due to early buckling of infill plates was considered. The ductility ratio was calculated as the ratio of the maximum displacement to the yield displacement (i.e.$\mu = \delta_{max}/\delta_y$). The maximum displacement ($\delta_{max}$) was defined as the top storey displacement at a drift ratio of 2.5% at least at one of the stories of the system. The yield displacement ($\delta_y$) was measured through the concept of equal plastic energy, so that the area enclosed by the idealized elasto-plastic curve was equal to that of the actual pushover curve, as depicted in Fig. 20. The results show that the stiffness of the SPSWs due to the introduction of the openings and LBE can be significantly increased (up to 56%). Generally, the ratio of the increase in the stiffness increases with the aspect ratio of the system and decreases with the height of the system. Moreover, based on the results in Tables 7 and 8, the ductility ratio of the SPSWs due to the introduction of the opening is partially decreased (up to 25%). Indeed, plastic deformation of infill plates is the main source of the SPSW ductility. Therefore, with the additional increase in the stiffness and strength of the frame and consequently, reduction in the participation of the plate action in the behavior of the system, the ductility ratio of the system will be decreased. However, the ratio of the decrease in the ductility does not change significantly with the height and aspect ratio of the system.

For multi-storey cases in which the openings are not repeated at every level and thus, are introduced only at arbitrary level(s), stiffness and ductility of the system lie, respectively, between the stiffness and ductility of its corresponding SPSWs without the openings and with the openings at every level.

**Table 8**
Effects of the introduction of the openings on the stiffness and ductility of SPSWs with L/h = 1.43 and different number of stories.

| # of stories, n | Model name | $K'$ (KN/mm) | $\mu'$ | Ratio | |
|---|---|---|---|---|---|
| | | | | $\frac{K'}{K}$ | $\frac{\mu'}{\mu}$ |
| 1 | 1S5L-W3 | 463.7 | 5.85 | 1.45 | 0.84 |
| 2 | 2S5L-W3 | 270.0 | 6.06 | 1.43 | 0.77 |
| 3 | 3S5L-W3 | 176.1 | 5.25 | 1.36 | 0.75 |
| 4 | 4S5L-W3 | 121.0 | 4.79 | 1.30 | 0.83 |
| 6 | 6S5L-W3 | 90.3 | 3.77 | 1.21 | 0.85 |
| 8 | 8S5L-W3 | 66.7 | 3.05 | 1.15 | 0.87 |

## 4. Conclusions

A number of single and multi-storey SPSWs with and without stiffened large rectangular openings used as doors and windows in buildings were analyzed and the results were utilized (a) to characterize the behavior of SPSWs with stiffened rectangular openings, (b) to study the effects of opening features as well as size of LBE and thickness of infill plates on the behavior of system and (c) to investigate the changes in the system behavior due to the introduction of the openings. The following can be concluded from this study:

- The procedure addressed by AISC Design Guide 20 for design of HBEs above and below the opening level due to neglect of additional shear forces imposed on the beams is not perfect. In fact, reaction forces from vertical LBE at the opening level imposed additional shear force and bending moment demands on the HBEs and thus, considering the effect of only one of these demands in the design, such as bending moment demand, similar to that addressed by the current design guide, may not necessarily result in a proper design in all cases.
- Special concern must be paid to the design of both the thickness of infill plates on either side of the opening and the size of LBE around the opening. Use of thicker or thinner infill plates or weaker profiles for the LBE can alter the yielding sequence in the SPSW and this way; it can affect the ductility and behavior of the system.
- Notably, the type, location and geometry of stiffened openings are not influential themselves on the system strength, although different LBE sizes required for different openings may have some effects (about 5% for the cases in this study).
- Although the ultimate strengths of infill plates before and after the introduction of the opening are almost the same, infill plates in SPSWs with the openings behave somewhat stiffer and yield at a relatively lower drift ratio. The stiffness and strength of the

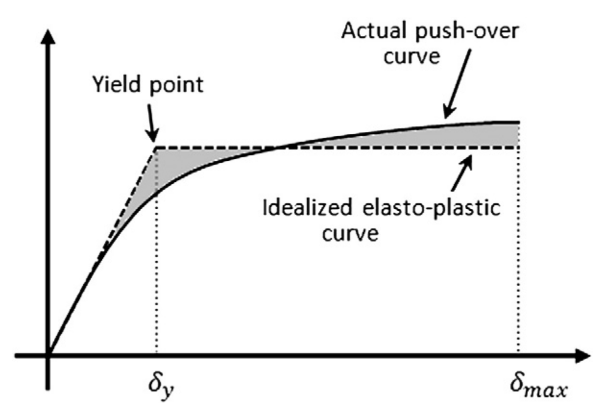


**Fig. 20.** Definition of a yield point.

frame due to the introduction of the LBE are also increased (up to 49% in terms of the strength).

- A slight increase in the ultimate strength of infill plates of the six and eight-storey SPSWs with the openings is observed (about 5 and 8%, respectively). It seems that the percentages tend to increase for taller SPSWs. This needs further investigation.
- The introduction of openings and LBE in a SPSW increases the ultimate strength of system (up to 30% for the cases in this study), and the ratio of the increase generally decreases with the aspect ratio and slightly increases with the height of the system.
- Considering the effect of early buckling of infill plates on initial stiffness, the stiffness of SPSWs with the openings is always higher than that of their corresponding SPSWs without the openings (about 15–56%). The ratio of the increase generally decreases with the height and increases with the aspect ratio of the system.
- The ductility ratio of SPSWs due to the introduction of stiffened openings is always decreased (about 7–25%).

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