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ENERGY DISSIPATION AND DUCTILITY OF STEEL PLATE SHEAR WALL WITH PERFORATION

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Abstract

Steel plate shear wall (SPSW) is known as an effective structural system in high rise building that provides lateral resistance against wind or earthquake. SPSW sometimes, needs to be perforated to provide access for human which may reduce the capability of SPSW in resisting the lateral load. This study investigated the effect of size and location of perforation to the lateral resistance of SPSW. This study was done numerically by varying the sizes and locations of perforation in the SPSW, while monitoring the horizontal displacement of the top side of SPSW. The first set of models had perforation of 1.2 m wide and 2 m high being placed at different location in the SPSW models, while the second set of models had varying sizes of perforation at the centre of the SPSWs. Both sets of the SPSWs were 4 m high with two different widths, which were 4 m and 6 m. Cyclic loadings were applied laterally for each SPSW model as according to ATC24 and the displacements at the top side of the SPSW model was obtained from the analysis. Hysteretic curves of all models were plotted to obtain the energy dissipation, lateral load capacity and ductility. It is found that perforation that is located nearest to the edge of the SPSW lowers the energy dissipation, ductility and lateral load capacity the most. Larger size of perforation of the SPSW caused larger reduction of the energy dissipation, ductility and lateral load capacity, while wider SPSW have larger values of energy dissipation, ductility and lateral load capacity.

Keywords: Steel plate shear wall, Perforation, Lateral Resistance, Energy Dissipation, Ductility l

Abstrak

Dinding ricih plat keluli (SPSW) dikenali sebagai system struktur berkesan di dalam bangunan tinggi yang memberikan rintangan sisi terhadap angin atau gempa bumi. SPSW kadangkala, perlu ditebuk untuk menyediakan laluan bagi manusia yang mungkin mengurangkan kebolehan SPSW dalam menahan beban sisi. Kajian ini menyiasat kesan saiz dan kedudukan tebukan terhadap rintangan sisi SPSW. Kajian ini telah dilakukan secara berangka dengan mengubah saiz dan kedudukan tebukan dalam SPSW, sementara mengawal anjakan sisi pada sisi atas SPSW. Set pertama model mempunyai tebukan 1.2 m lebar dan 2 m tinggi yang diletakkan pada kedudukan bebeza di dalam model SPSW, sementara set kedua model mempunyai saiz tebukan berbeza di tengah SPSW. Kedua set SPSW adalah 4 m tinggi dengan dua kelebaran berbeza, iaitu 4m dan 6 m. Beban berkitar dikenakan secara sisi pada setiap model SPSW dengan mematuhi ATC24 dan anjakan pada sisi atas model SPSW telah diperolehi dari analisis. Lengkokan hysteresis bagi semua model telah diplot untuk memperolehi perlesapan tenaga, muatan beban sisi dan kemuluran. Adalah didapati tebukan yang terletak paling hampir dengan sisi SPSW mengurangkan perlesapan tenaga, kemuluran dan muatan beban sisi paling tinggi. Saiz tebukan SPSW lebih besar menyebabkan pengurangan perlesapan tenaga, kemuluran dan muatan beban sisi lebih besar, sementara SPSW yang lebih lebar mempunyai nilai perlesapan tenaga, kemuluran dan muatan beban sisi yang lebih besar.

Kata kunci: Dinding ricih plat keluli, Penebukan, Rintangan Sisi, Lesapan Tenaga, Kemuluran

1.0 INTRODUCTION

Steel plate shear wall (SPSW) is an effective earthquake resistant structural system that has been used for more than thirty years. SPSW comprises a thin infill steel plate which acts as a web plate and boundary elements that are bolted or welded to the infill steel plate. The infill steel plate is enclosed by the boundary elements and is fabricated from mild steel or low yield steel while the boundary elements which are beams and columns, are fabricated from high tensile steel. As a result, the infill steel plate yields first with the propagation of yielding zone, while the beam-to-column connection yields at near-ultimate stage, which is a good seismic resistance characteristic (Chen & Jhang, 2006). Further, excellent response to cyclic load, both in elastic and inelastic range is achieved if the ratio of width-to-thickness or depth-to-thickness of the SPSW is kept less than 100 (Chen & Jhang, 2006). The ability of SPSW to resist earthquake mainly comes from the energy dissipating capacity of the web plate under extreme cyclic loading, high stiffness and desirable ductility (Paslar et al, 2020 and Liu et al, 2020). The energy dissipation capacity of the shear steel plate can be significantly increased by the installation of stiffeners, which on the other hand, does not improve the shear strength of the SPSW (Sabouri-Ghomi et al, 2012). In comparison with reinforced concrete shear wall, SPSWs is significantly faster to construct and much lighter and, thus shorten the construction time which lowers the total cost of the project. The lighter steel components of SPSW reduce the columns and foundations demand and further, reduce the mass of the structure.

Perforation of the SPSW may be required to allow human and utility access. Multiple circular perforation reduces the shear strength of SPSW where increased number of perforation and diameter of the perforation decrease the shear strength of SPSW. (Bhowmick et al., 2014). However, circular perforated SPSW that was stiffened diagonally has shear strength that was close to the unstiffened SPSW without perforation, and further, increased ductility ratio by 14% compared to the unstiffened SPSW (Alavi and Nateghi, 2013). Further, multiple circular perforation made on thick infill steel plate has the advantage of reducing the demand that is induced to the boundary elements due to the infill plate yielding, which is a better solution than using thin infill plate that causes construction difficulties. (Chan et al, 2011).

The strength of the SPSW is significantly reduced as large-sized perforation is used, and it is recommended to have opening of sizes less than 15% of the area of the steel plate (Moradi et al., 2020 and Khan & Srivastava, 2020). However, the ultimate strengths of the SPSW is not affected while the stiffness is increased by 15 to 56 percent if the rectangular perforation that served as window or door is stiffened (Hosseinzadeh and Tehranizadeh, 2012). The use of stiffener on SPSW with rectangular opening between SPSW and the vertical boundary elements had caused the link beam, which is the beam that joined the SPSW to the vertical boundary element, to yield, and thus dissipates energy, instead of the traditional phenomena, where infill steel plate yields and dissipates energy (Mu and Yang, 2020). Thicker infill plate reduces the stiffness of the perforated SPSW (Moradi et al., 2020) while the usage of corrugated steel as infill plate could increase both initial stiffness and ductility of the perforated steel shear wall by 30 to 50 percent (Farzampour et al.,2015). Larger aspect ratio of the shear wall could improve the initial stiffness and ultimate shear strength especially when the perforation of the wall is large (Farzampour et al.,2015). The reduction of the shear load capacity is minimized while increment of the energy dissipation is maximized when the SPSW is perforated with either horizontal rectangular or square perforation instead of the vertical rectangular perforation (Samat et al, 2020). Rectangular opening that was centrally placed at the mid height of the SPSW, had the least energy dissipation compared to when the opening was placed at the bottom left or at the top right of the SPSW (Sabouri-Ghomi et al, 2012), while another research concluded that the best position of the perforation is at the central-bottom of the infill plate. (Khan & Srivastava, 2020)

Previous research shows that perforation caused shear load capacity of SPSW to reduce. However, perforation of SPSW to allow human access is unavoidable, and it is important to know the position and the size of perforation that causes minimal reduction of both shear load capacity and energy dissipation of the perforated SPSW so that the perforated SPSW that is employed in the design of high rise building still serves the intended purpose which is resisting the seismic excitation. Thus, the objective of this research is to determine the effect of location and size of rectangular perforation to shear load capacity and energy dissipation of SPSW. This study was done based on numerical simulation that was carried out using Abaqus software. The perforation is placed at the bottom of the SPSW with varying location from the edge of the infill plate to the centre of the infill plate.

2.0 METHODOLOGY

SPSW consists of mild steel plate where its edges are joined to either vertical or horizontal boundary element. In this study, A36 steel was used for the steel plate while W360 x 33 ASTM A992 steel was used for both the vertical and horizontal boundary elements. Boundary elements prevent the steel plate from being imposed by gravity load as the steel plate function is to resist only lateral load by forming tension field that acts like a diagonal brace.

The dimensions of the SPSW studied are 5 mm thick, 4 m high with two different width of 4 m and 6 m. The SPSW was restrained at z-axis at the top to prevent out-of-plane deformation. Cyclic load which is shown in Figure 1, is deformation control load as in accordance to ATC24 that was applied along the vertical boundary elements at A. Lateral displacement at B was determined by analysis from Abaqus software. The location of points A and B are shown in Figure 2. Hysteretic curve that shows the relationship between cyclic load and lateral displacement were plotted, and energy dissipation was calculated based on the hysteretic curve.

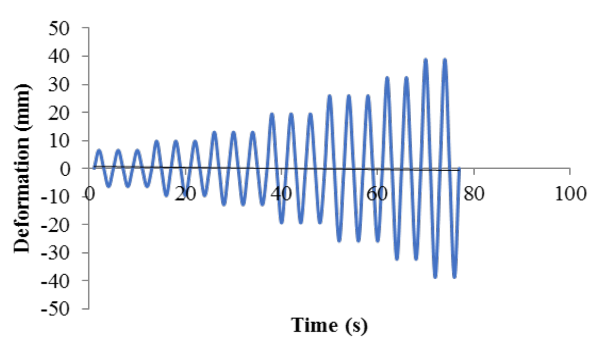

Figure 1 Deformation control load that was applied to the SPSW models .

2.1 Location of Perforation

The first set of the perforated SPSW models were designed to study the effect of the location of the perforation to energy dissipation, ductility and lateral load capacity of the SPSW. The same size of perforation which was 1.2 m wide by 2 m high, was used for all models, but was located at different place in the steel plate, namely, the distance of the perforation from the left of the SPSW, *s* as illustrated in Figure 2. Table 1 tabulates the distance of the perforation from the left of the SPSW, *s* for different SPSW models.

Table 1 Distance of perforation from the left of the SPSW for different type of SPSW models.

Steel Plate Shear Wall (SPSW)		Distance of perforation from the left of SPSW, *s* (m)				
		Plate 1	Plate 2	Plate 3	Plate 4	Plate 5
Breadth (m)	4	0.2	0.4	0.9	1.4	-
	6	0.2	0.4	0.9	1.4	2.4

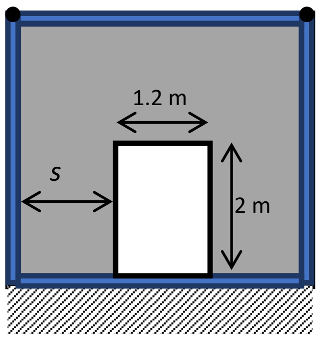

Figure 2 SPSW model with perforation at different location.

2.2 Size of Perforation

The second set of the SPSW models had varying perforation size. The perforation which was placed at the centre bottom of the SPSW, had the same width but different height of the perforation, h_p as shown in Table 2 and is illustrated in Figure 3. SPSW models without perforation were also analysed for comparison purposes.

Table 2 Height of perforation.

SPSW		Height of perforation, h_p (m)		
		Plate A	Plate B	Plate C
Breadth (m)	4	1	2	3
	6	1	2	3

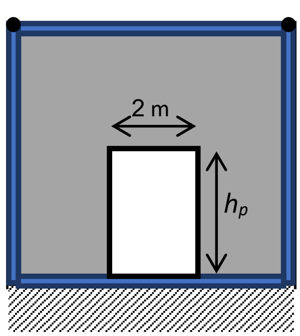

Figure 3 SPSW model with different height of perforation.

3.0 RESULTS AND DISCUSSION

Seismic resistance structure has the ability to deform and dissipate energy which prevents the structure from reaching ultimate failure during an earthquake. Energy dissipation is presented by the area of the hysteretic loops while ductility is defined as the ratio of the maximum displacement to displacement at yield. Lateral load capacity of the model is defined as the maximum lateral load that can be applied to the model. Energy dissipation, ductility and lateral load capacity were obtained for all models and tabulated in Table 3 and Table 4.

3.1 Location of Perforation

Figure 4 shows the result of energy dissipation at various location of perforation. It is observed that the energy dissipation increased as the distance of perforation, *s* in-creased. Comparing with the energy dissipation of the control model which is the unperforated SPSW models, the energy dissipation was reduced by 50 percent and 45 percent when the perforation is made at 0.2 m away from the left of the SPSW for 4 m wide SPSW and 6 m wide SPSW, respectively (Table 3). As the distance from the left of the SPSW, *s*, was increased to the maximum value which is the case when the perforation was placed exactly at the center of the SPSW, (where *s* equals to 1.4 m and 2.4 m for 4-m-wide SPSW and 6-m-wide SPSW, respectively), the energy dissipation increased to the maximum values, compared to the rest of the perforated SPSW models such that percentage of reduction of energy dissipation when compared to the control SPSW model becomes only 24.7 percent and 0.47 percent, for 4 m wide SPSW and 6m wide SPSW, respectively.

Figure 4 shows energy dissipation value as the distance of perforation from left of SPSW was increased as well as the percentage of difference of energy dissipation between SPSW with 4m and 6m wide. The energy dissipation of the 6 m wide unperforated SPSW is only 1.4 percent higher than the 4 m wide unperforated SPSW as shown in Figure 4. For the perforated SPSW, the energy dissipation varied between -0.9 percent to 18 percent when width of SPSW was increased from 4 m to 6 m.

Lateral load capacity was reduced by 47 percent and 40 percent when the perforation was placed 0.2 m from the left of the SPSW for 4 m SPSW and 6 m SPSW, respectively (Table 3). The lateral load capacity of the perforated SPSW increased when the distance, *s*, increased as shown in Figure 5. The maximum lateral load capacities which were 67 percent and 75 percent of the lateral load capacities of the control SPSW with width of 4 m and 6 m, respectively, were obtained when the perforation was placed at the centre of the SPSW. Both the control and perforated SPSWs increased its lateral load capacity between 24 percent to 33 per-cent when the width of the SPSW was increased from 4m to 6 m.

Similar to the behaviour of energy dissipation and lateral load capacity, ductility increased with the increase of distance of the perforation, *s*, and became maximum when the perforation was at the centre of the SPSW (Figure 6). Ductility of 6 m wide SPSW was always higher than the one of 4 m wide SPSW, and became larger than ductility of the unperforated

SPSW when the distance, *s*, of the perforation from the left of the SPSW was between 0.9m to 2.4m.

In general, energy dissipation, lateral load capacity and ductility were at the minimum values when the perforation was the closest to the left side of the models and the maximum when the perforation was at the centre of the models. This is due to the out of plane buckling that occurred when the perforation was closest to the left of the model as shown in Figure 7(b). As the perforation was moved to the centre of the model, no out of plane buckling was seen (Figure 7(c)). Further analysis was done by using hysteretic curve as shown in Figure 8. The out of plane buckling caused the hysteretic curve to become unsymmetrical as shown in Figure 8(b) where stiffness degradation was observed to occur at the lower part of the hysteretic curve. The hysteretic curves for both control model and model with perforation at the centre of the model (Figure 8(a) and 8(c)) are symmetrical as out of buckling did not occur.

Table 3 Energy dissipation, lateral load capacity and ductility of the SPSW models with different location of perforation.

Distance of perforation, *s* (m)	**Energy dissipation** (kJ)		**Lateral load capacity** (kN)		**Ductility**	
	4 m wide SPSW	6 m wide SPSW	4 m wide SPSW	6 m wide SPSW	4 m wide SPSW	6 m wide SPSW
control	4198	4258	5151	6768	4.6	4.7
0.2	2083	2340	2709	4067	3.2	3.5
0.4	2487	2464	3108	4254	3.6	3.8
0.9	2867	3384	3241	4809	4.1	4.9
1.4	3163	3580	3468	4569	4.6	5.5
2.4	-	4238	-	5080	-	6.2

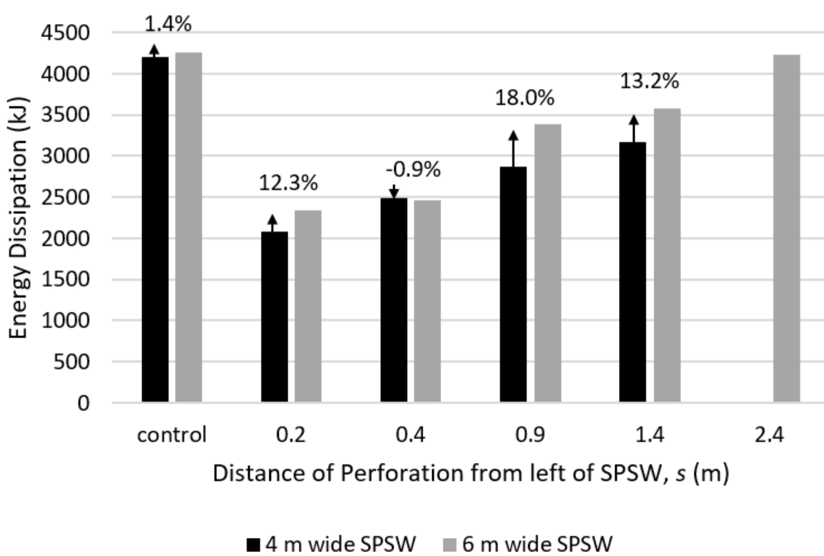

Figure 4 Behaviour of energy dissipation with location of perforation for different breadth of SPSW.

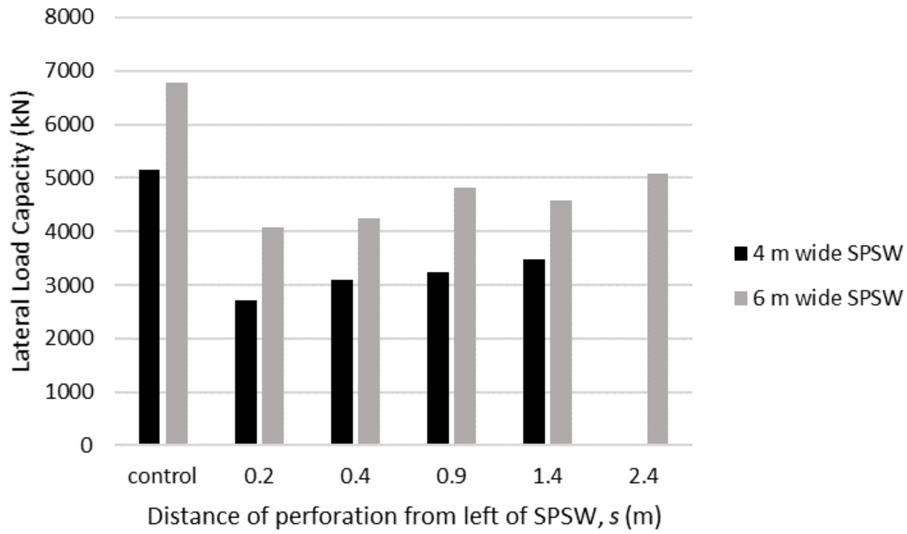

Figure 5 Behaviour of lateral load capacity with location of perforation for different width of SPSW.

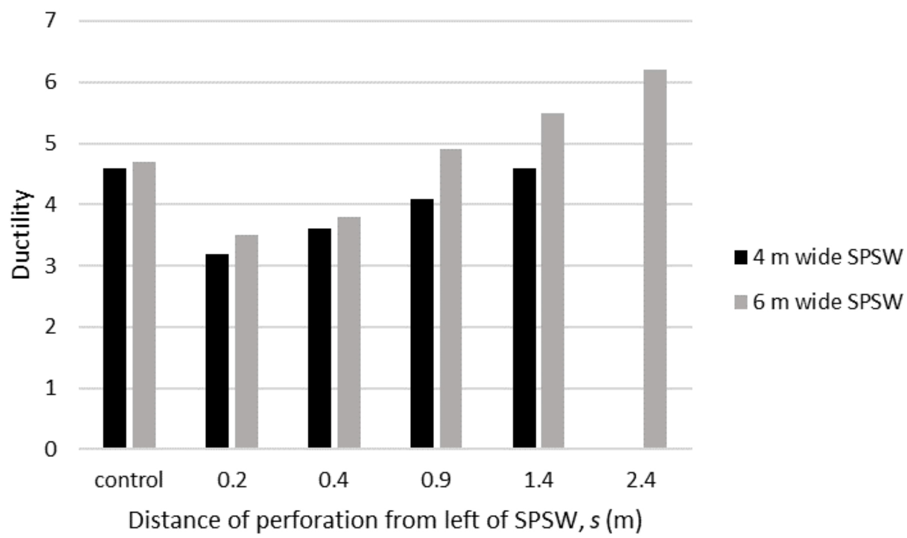

Figure 6 Relationship of ductility and location of perforation.

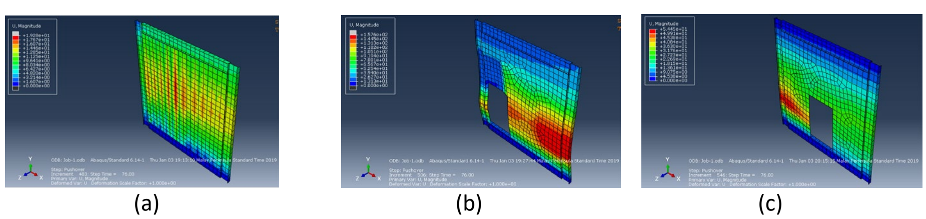

Figure 7 Deformed Shape of 4 m wide SPSW (a) control model (b) model with perforation at 0.2m away from the left of the SPSW (c) model with perforation at the centre of the model.

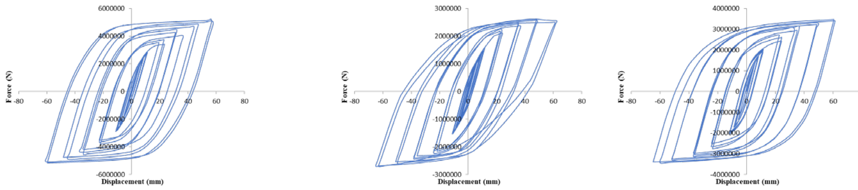

Figure 8 Hysteretic curve of 4 m wide SPSW (a) control model (b) model with perforation at 0.2m away from the left of the SPSW (c) model with perforation at the centre of the model.

The same behavior is observed for the 6 m wide SPSW, where out of plane buckling occurred when the perforation was located closest to the side of the SPSW, while no out of plane buckling is observed when the perforation was at its center. As a result, the hysteretic curve of the 6 m wide SPSW became unsymmetrical when the perforation was the closest to the side of the SPSW.

3.2 Size of Perforation

Energy dissipation, lateral load capacity and ductility of SPSW with different size of perforation are tabulated in Table 4. The existence of 1 m high perforation caused the energy dissipation of the 4 m wide SPSW to reduce by 13.5 percent and, and 6 m wide SPSW to increase by 5 percent. (Table 4). Then, the energy dissipation decreased as the height of perforation, h_p was increased for both SPSW model with 4 m and 6 m width (Figure 9). As the height of perforation, h_p increased, the size of perforation increased, and thus reducing the stiffness of the SPSW model. Energy dissipation of 6 m wide SPSW is higher compared to 4 m wide SPSW due to its higher lateral stiffness provided by the larger width it had and was slightly affected by the perforation. The smallest perforation had caused the 6 m wide SPSW to increase ductility vastly, but reduced the lateral load capacity moderately which caused the energy dissipation to increase slightly. Energy dissipation of the 6m wide SPSW was reduced significantly only when the largest perforation which was 3 m high was made where ductility reduced to a value almost equal to the ductility of the control model while the lateral load capacity dropped to 70 percent of the lateral load capacity of the control model.

Table 4 Energy dissipation, lateral load capacity and ductility of SPSW with different size of perforation

Height of perforation , h_p (m)	**Energy dissipation** (kJ)		**Lateral load capacity** (kN)		**Ductility**	
	4 m wide SPSW	6 m wide SPSW	4 m wide SPSW	6 m wide SPSW	4 m wide SPSW	6 m wide SPSW
control	4198	4258	5151	6768	4.6	4.7
1	3620	4470	3865	5379	5.2	6.5
2	3163	4238	3468	5080	4.6	6.2
3	2751	3909	3024	4737	3.2	4.8

Further, the existence of 1 m high perforation caused the lateral load capacity to reduce by 25 percent and 20 percent of the 4 m wide and 6 m wide SPSW, respectively (Table 4). The lateral load capacity decreased when the size of the perforation increased as shown in Figure 10. SPSW with 6 m width also have significantly higher lateral load capacity compared 4 m wide SPSW.

Interestingly, the existence of 1 m high perforation caused the ductility to increase for by 13 percent and 38 percent of the 4 m wide and 6 m wide SPSW, respectively (Table 4). The existence of small perforation may have caused the SPSW to have larger maximum displacement, but maintaining the same displacement at yield, and as a result, the ductility increased. Ductility decreased as the size of perforation increased. Larger perforation may have caused both the maximum displacement and displacement at yield to increase, which results in lower value of ductility. Figure 11 shows that the ductility of 6 m wide perforated SPSW was always higher than the 4 m wide perforated SPSW. The larger width of 6 m wide perforated SPSW allows larger maximum displacement which results in higher ductility compared to 4 m wide perforated SPSW.

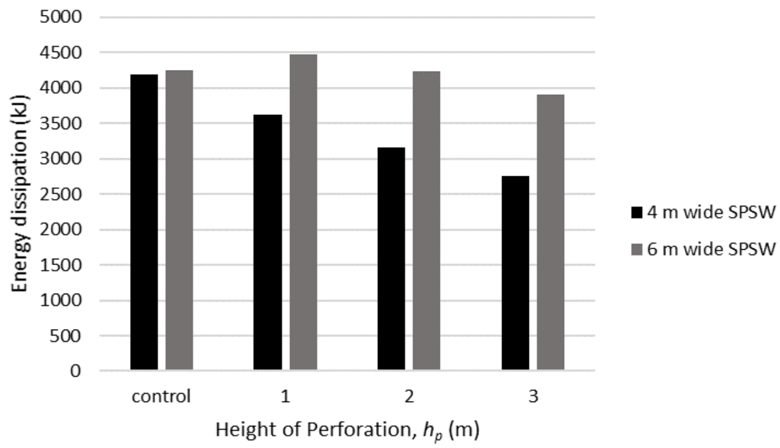

Figure 9 Energy dissipation and height of perforation for different width of SPSW.

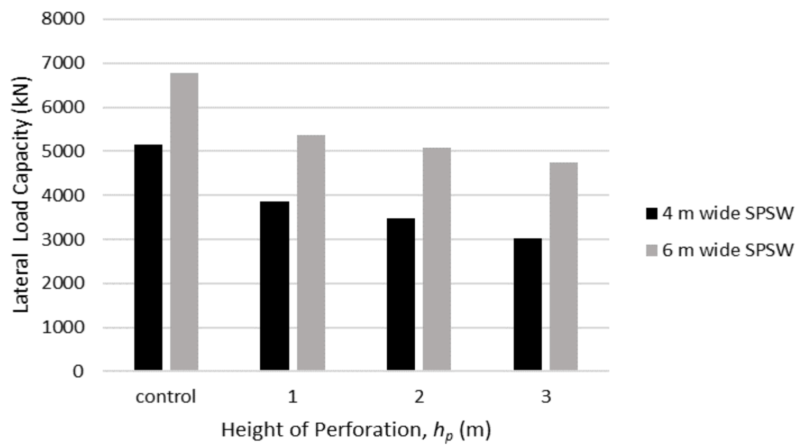

Figure 10 Behaviour of lateral load capacity with size of perforation.

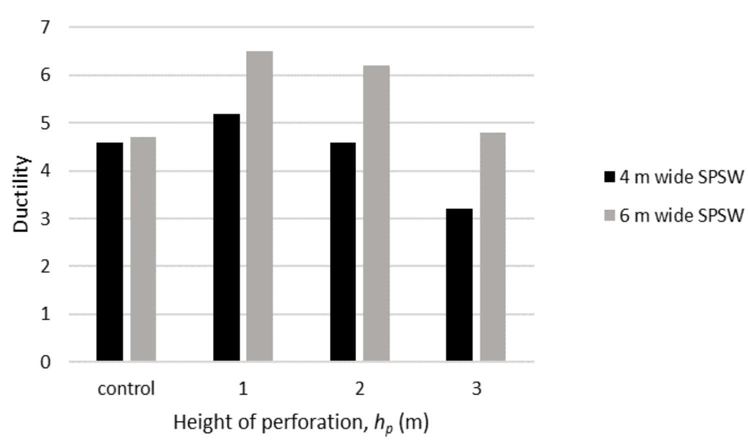

Figure 11 Behaviour of ductility with size of perforation.

4.0 CONCLUSIONS

The behaviour of steel plate shear walls (SPSW) with different location and sizes of perforation for 6 m and 4 m wide SPSW have been investigated. The following observations and conclusions are drawn from the present study:

1) The energy dissipation, ductility and lateral load capacity are affected by the different location of the

perforation for the SPSW, where perforation that is closer to the acting force has lower energy dissipation, ductility and lateral load capacity.

2) The increase in size of perforation for SPSW causes the energy dissipation, ductility and lateral load capacity to decrease.
3) Wider perforated SPSW has higher energy dissipation, lateral load capacity and ductility.
4) The overall study suggests that the optimum location of perforation for SPSW is at the centre of the SPSW with smaller sizes of perforation. Energy dissipation of wider SPSW was only slightly affected by the perforation and thus, its capability to reduce the transmission of earthquake load to the structure was not impaired.

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