THE STRENGTH AND STIFFNESS OF RING-SHAPED STEEL PLATE SHEAR WALLS: EXAMINATION AND ANALYSIS

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Abstract

Steel plate shear wall (SPSW) is considered a suitable lateral load-resisting system in new and retrofit structures. This system is nevertheless plagued with a plethora of challenges. One of its major drawbacks is the need to use sheets with very low thickness given the required force in the design, which, in addition to the complications in installation, does not provide the minimum dimension needed for welding. In this research, the laboratory samples tested by Egrova et al. (2014) were modeled and analyzed in Abaqus to measure the accuracy and efficiency of the proposed model. The results showed that the change in the parameters of ring-shaped steel plate shear walls (RS-SPSW) has almost the same effect on the strength and stiffness of the wall. As such, evidence suggests that it is difficult to design the wall by altering the parameters of ring-shaped steel plate shear walls, separately and with a different purpose in terms of stiffness and strength. Nevertheless, changing the number of rings in a frame more effectively provides the capacity to have a design with different stiffness and strength. The strength of RS-SPSWs can simply be improved by increasing the thickness, decreasing the ring radius, increasing the number of rings, and increasing the ring width. Moreover, the strength of RS-SPSWs can be optimized by increasing the thickness, reducing the width of the connecting link, and increasing the width of the ring. Ultimately, increasing the thickness, decreasing the width of the connecting link, and increasing the ring width heightens the rate of energy dissipation.

Keywords: shear wall, ring-shaped steel plate shear walls, wall strength, wall stiffness

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Introduction

Until very recently, steel plate shear walls have been mainly designed with thin plates with permissible plate buckling. Past research shows that steel plate shear wall has a significant post-buckling capacity and significant energy is dissipated in the formation of a tensile field. Steel plate shear wall is composed of a simple thin infill plate with elements acting as the two columns, called vertical boundary elements, and two beam elements, called horizontal boundary elements (Saltykova, 2021). The laboratory-based evidence suggests that the simple steel plate shear wall acts like a tensile brace under lateral loads, including ground movement and seismic force. As stated in the design regulations, the use of tensile braces in seismic areas is not allowed owing to the lack of required strength when changing the direction of force in reciprocating loads.

Thorburn et al. (1933) were the first to invent a method for evaluating the high post-buckling strength in metal plates. In this analytical method, the force created in the buckling region is replaced by axial members that have only tensile strength. Cassese et al. (1993) examined the seismic behavior of steel plate shear walls without stiffeners with thin plates. Schumacher et al. (1992) also examined the behavior of steel plate shear walls without stiffener at the beam-column junction. Berman and Bruneau (2005) designed experiments to study braced frames and steel plate shear walls. The plasticity in the wall was equal to 3. According to the results, 62% of the total energy dissipation was owing to the presence of plates in the wall. While the total energy dissipated in the wall was less than one-fifth of a simple steel plate shear wall. Tipping and Stojadinovic (2003) proposed a type of steel plate shear wall that used a light metal sheet bolted to the side elements of the light frame type. The findings of the experiments revealed that in all the samples, damages were only witnessed at the adjacency of the screws owing to the warping of the plate. Two samples were designed to examine the effect of adding corrugated metal sheets to both sides of the wall. The result of the experiment indicated that adding steel sheets doubles the shear strength. Robert and Sabouri-Ghomi (1992) conducted tests on six samples made of the unstiffened single-perforation plate under quasi-static cyclic loading. The findings revealed that all the panels had a balanced hysteresis behavior. All the frames showed adequate ductility in the first four loading cycles without any reduction in load-carrying capacity.

Furthermore, Vian and Bruneau (2005) conducted experiments to evaluate the efficiency of perforated steel plate shear walls. The elastic strength and stiffness of the sample compared to the plain plate in the same dimensions were found to be 32.2% and 31.2%, respectively. Moghimi and Driver (2011) examined the effect of perforation on a steel plate shear wall and compared the results with a normal shear wall. The results of the experiment showed that although perforation of the wall decreases the shear capacity, it doesn’t alter the required capacity for column design, the effects of which are more pronounced for higher floors (Sadovnikova, 2022). Hitaka et al. (2000) conducted experiments on a steel plate shear wall with slits, in which the studied parameters were the stiffness percentage of the beam-to-column connection and the strength and stiffness of the wall. Hitaka and Matsui (2003) proposed the steel plate shear wall with vertical slits, in the space between which the bending links that make the wall have a ductile response. Cortes and Liu (2008) examined steel silt panel configurations under lateral forces. Borchers et al. (2010) conducted experiments on walls equipped with buckling-resistant channels to reduce buckling in plates with longer links. Cortes and Liu (2008) conducted experiments on slit steel plate shear walls with Buckling resistant channels (panel BR). The obtained hysteresis diagram indicated solid and balanced behavior.

Egorova et al. (2014) proposed a novel steel plate shear wall, in which rings were shaped using cuts in the sheets. The rings were connected diagonally by connecting at 45-degree angles. That is, the main idea of this type of shear wall is the use of rings. In this wall, called a ring-shaped steel plate shear wall (RS-SPSW), applying lateral deformation to the wall causes the ring to change shape from a circle to an ellipse. But considering that, unlike rectangular-shaped components, the deformation in the axial direction where the rings elongate is equal to the deformation in the axial direction where the ring shortens, the slack in the direction perpendicular to the tension field is essentially eliminated, thereby resisting out-of-plane buckling.

In using ring-shaped shear walls, simple connections between beam and column can be used, and rigid bending connections are not required. Because in this type of wall, unlike a simple steel plate shear wall, the wall is not welded directly to the frame, which allows the wall to be used in a plethora of beam-column configurations. One of the advantages of steel plate shear walls is the high number of variables, which allows high freedom in tailoring the shear wall according to the needs of the region and the desired structure (Morjani, et al., 2021). This is simply achieved by altering the parameters to meet the required hardness, strength, and ductility separately. The idea behind using ring-shaped steel plate shear walls is to reduce buckling outside the wall plane by using ring-shaped designs.

Given the aforementioned discussion, the purpose of the current research was to examine ring-shaped steel plate shear walls so that this type of steel plate shear wall can be used more in practical designs.

Research Methodology

Ring-shaped steel plate shear walls (RS-SPSWs), were first proposed by Egrova et al. (2014) as an innovative method to optimize energy dissipation in the wall and significantly increase the efficiency of the steel plate shear wall, which were successfully put to test in numerous experiments.

As such, the first task the authors of the current research had to address was to evaluate and hence confirm the efficiency and accuracy of the modeling and analysis method of software samples of the original study, the parameters from which were modeled, and eventually analyzed, in Abaqus software.

small-scaled dimensions of the original design, i.e., that from Egrova et al. (2014), were employed for the study. The laboratory samples were only downsized to still exhibit the characteristics of ring-shaped steel plate shear walls in normal dimensions. This experiment was conducted in the laboratory of the University of Virginia to prove the idea of ring-shaped steel plate shear walls by examining its cyclic behavior and uncovering potential buckling modes, and to validate the proposed relationships in practice. In this experiment, MTS 243.60 hydraulic actuator, with 650kN pressure and 1015kN tension application, was used to apply force and deform the wall through the necessary shear deformation by its free end. The fixed end on the right side of the figure is connected to the ground by steel bolts, creating a rigid support condition. The manufactured sample is closed by its 4 metal wings on the sides between two sheets connected to the side elements, by steel screws to create a full grip and exclude slacks during the test. It should be noted that the fixed side legs are welded to the base by two braces, in the direction perpendicular to the sheet, to avoid any deformation of the base in the direction perpendicular to the sheet. Figure 1 illustrates an overview of the sample.

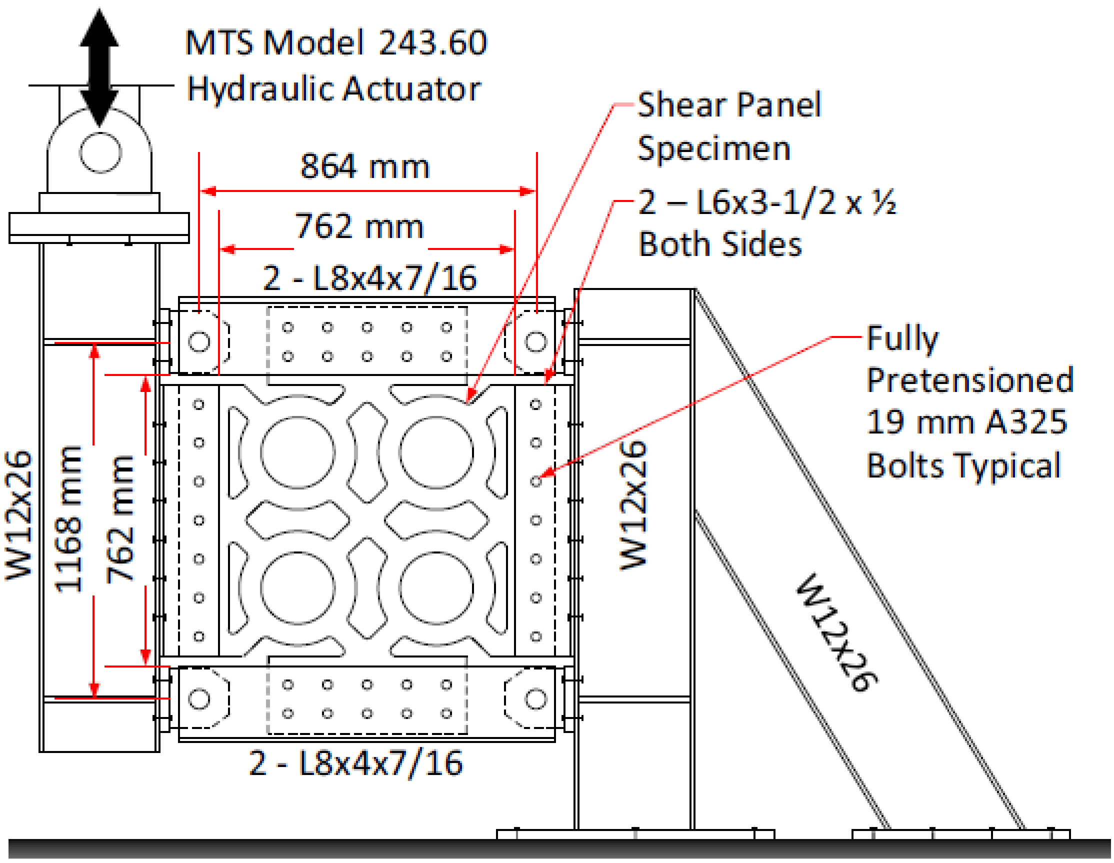

Figure 1: Overview of the test system (Egorova et al. 2014)

The loading protocol was derived from the ATC-24 regulation. For the current study, the angle of shear deformation at the moment of flow (δy/a) is considered equal to 0.5, and the value of a, which is the length of the test sample plate, is considered equal to 864mm. The values of the target displacement, the number of rounds, and shear deformation in each displacement step are obtained according to Table 1.

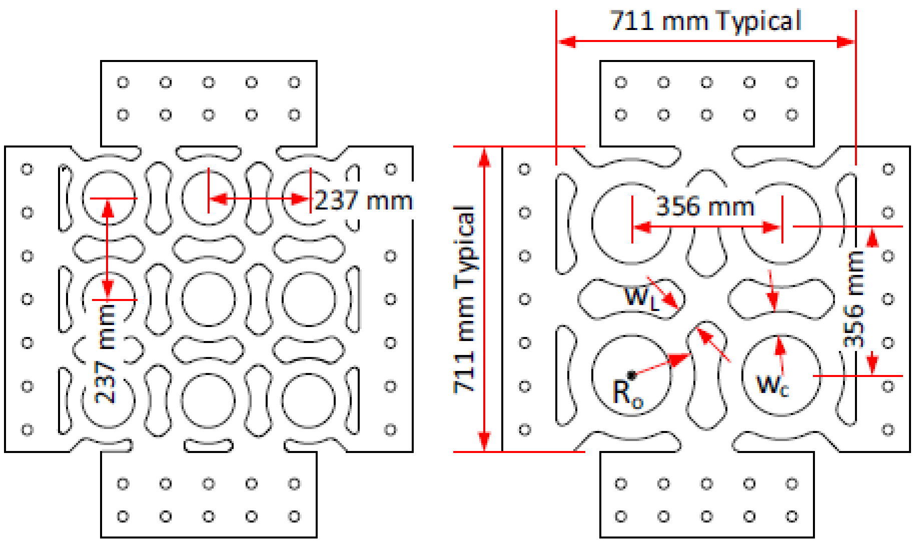

Figure 2: Overview of laboratory samples (Egorova et al. 2014)

It should be noted that the two parameters of Ro/t and Wc/t represent the thinness of the ring and the parameter a/t indicates the overall degree of wall thinness, all of which are employed as general measures of the non-dimensional characteristics of RS-SPSWs.

Specifications of modeled software samples

In this study, samples with different characteristics were designed to examine the features of ring-shaped steel plate shear walls in real dimensions, the aim of which was to evaluate the effects of wall properties such as ring diameter, the thickness of ring-shaped steel plate shear walls, and width of rings and connecting links, among others, on strength and stiffness.

Input parameters

The thickness of ring-shaped steel plate shear walls (t):

The thicknesses of the research shear wall plate were respectively 12mm, 16mm, and 20mm. These values can be argued to encompass a wide range, the analysis which enables higher accuracy and less error regarding the effect of thickness on the output of the samples. Preliminary predictions show that this change in thickness can change the value of wall strength in the range of 500kN~2700kN.

The radius of the outer rings (Ro):

The outer radius of the rings used in the design of the samples were respectively 200mm, 250mm, 400mm, and 600mm. It should be kept in mind that, for the walls designed using the minimum Ro of 200mm, the shear length of the wall increases as the outer diameter decreases, effectively leading to heightened production costs. On the other hand, walls designed at the upper limit of this range, that is 600mm, demonstrate the proper configuration of the annular shear wall that would enhance the lateral torsional buckling potential.

Width of rings (Wc):

The change in the value of the width of the rings used in the design of the walls is accounted for using the ratio of the outer radius of the ring to the width of the ring (Ro/Wc) and applied in the design of the samples. This ratio (Ro/Wc) represents the thinness of the ring, as the alteration in this parameter would change the buckling behavior of the wall. The ratios selected for this research were 2, 2.5, 3, and 3.5. There are two main reasons behind selecting these values. First, very wide rings would not easily enter the elastic region and flow, which would hence mitigate the dissipated energy consumed and lead to inappropriate cyclic behavior. Second, very thin rings cause early lateral torsional buckling in the wall and increase the fading effect in the hysteresis diagram of the wall.

Width of connecting links (Wl):

It is expected that the link width parameter is effective on the amount of axial plastic deformation of the connecting links, which in turn leads to degradation of the cyclic behavior of the wall. This parameter is also applied as the ratio of the radius of the outer ring to the width of the connection link (Ro/Wl) introduced in the design of the samples. The lower limit value of this range has been chosen considering that the width of the thin connection link reaches the plastic region earlier.

Output Parameters

Stiffness of the RS-SPSWs

To calculate the stiffness of the RS-SPSWs, each of the modeled samples is subjected to uniform loading. The force-displacement diagram has been extracted up to about 4% drift. Considering that the stiffness of the wall is equal to the initial slope of the force-displacement diagram, the slope of the line obtained from two points of origin (0,0) and point a is considered as stiffness. In choosing the location of point a, to increase the accuracy and prevent the possible errors generated in the software model in the initial moments of loading, this point is before the moment of wall flow and after ½ the distance of (0,0) and the wall flow. As such, Figure 3 shows the methods employed to evaluate the stiffness of the RS-SPSW

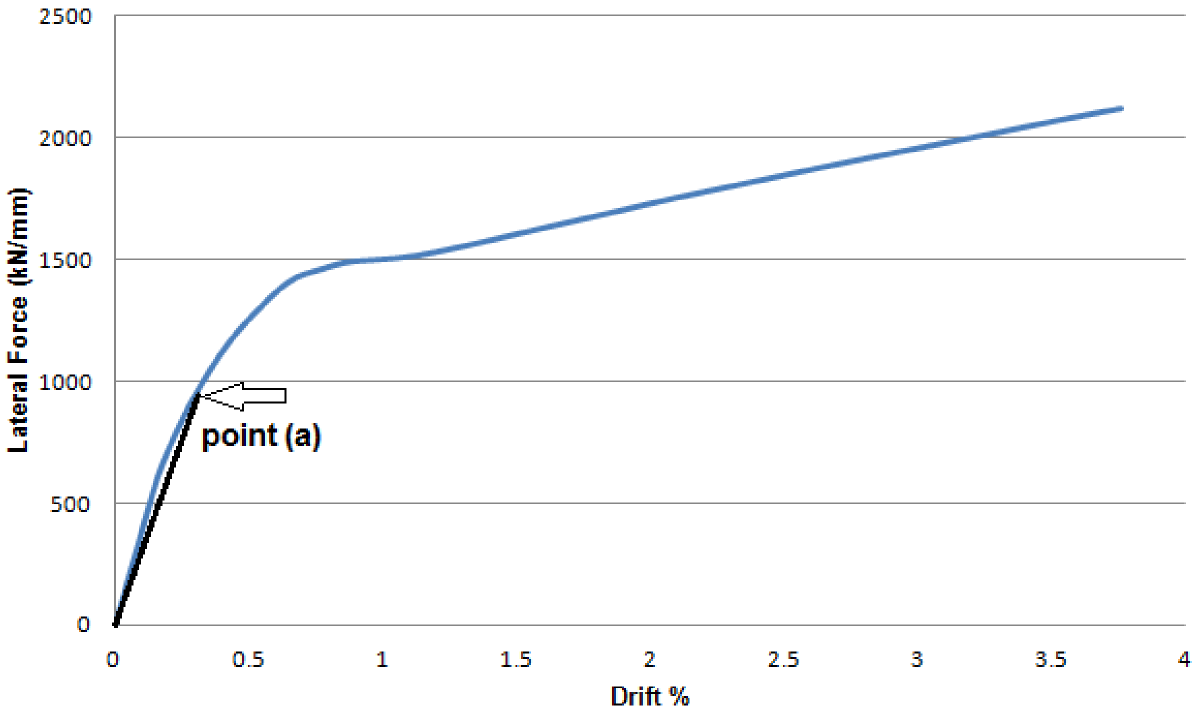

Figure 3: The point representing the stiffness of RS-SPSWs in software examples

Strength of the RS-SPSWs

The value of steel plate shear wall strength is equal to the amount of applied force required at the moment the wall flows or the moment plastic joints are created in the wall. From this point onwards, a noticeable and significant decrease in the slope of the graph is visible. This significant reduction in stiffness is attributed to the formation of the first plastic joint, followed by the formation of other plastic joints, leading to an extreme decrease of stiffness as the test continues. But with the progress of the test, the sample enters the re-hardening area and the strength increases again. Yet, owing to the presence of plastic joints, the slope of the graph, that is, the stiffness of the wall exhibits a significant decrease compared to the beginning of the test. To calculate this strength, the force-displacement diagram of each sample under uniform loading must first be obtained, after which the corresponding points on the diagram are found at drifts of 0.75% and 1%.

Extending the line created by connecting these two points and intersecting it with the line obtained for stiffness from the previous section results in point (b), which represents the strength of the wall. These steps are shown schematically in Figure 4.

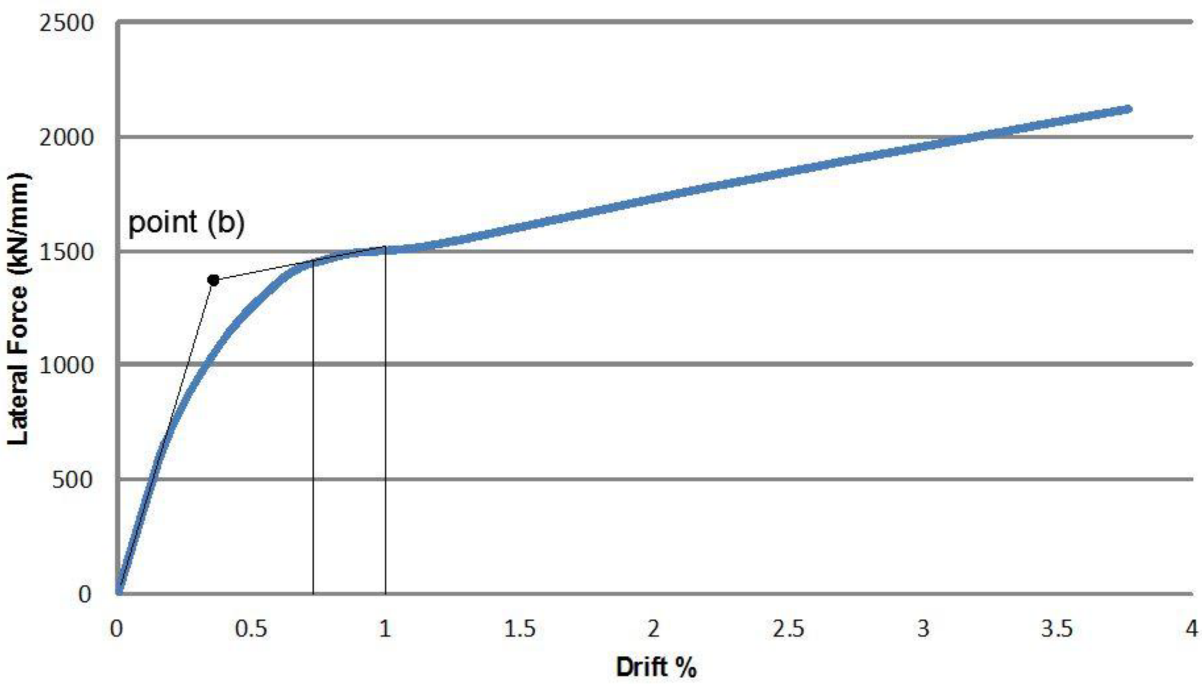

Figure 4: Calculating the strength of steel plate shear wall in software examples

Software models

In this section, all the designed and modeled examples in the software are summarized in the relevant tables. The following software samples are mainly designed to investigate the effect of wall thickness. For the first set of models, all parameters are fixed, and only the thickness parameter changes.

Table 1: The first set of software samples

	T(MM)	RO(MM)	RO/WC	WC(MM)	RO/WL	WL(MM)	RO/T
A1	**20**	**250**	**3.3**	**75.7**	**2**	**125**	**12.50**
A2	**16**	**250**	**3.3**	**75.7**	**2**	**125**	**15.63**
A3	**12**	**250**	**3.3**	**75.7**	**2**	**125**	**20.83**

The following set of models is mainly designed to examine the effect of outer radius (Ro). As such, two parameters of Ro/WL and Ro/WC are assumed constant while other values are altered with the change of Ro and t. Given that outer radius and thickness are two parameters that are concurrently effective, different values have been considered for the parameters.

Table 2: The parameters of the second set of software samples

	T(MM)	RO(MM)	RO/WC	WC(MM)	RO/WL	WL(MM)	RO/T
B1	16	600	3.3	181	2	300	37.50
B2	20	400	3.3	121	2	200	20.00
B3	12	200	3.3	60	2	100	16.67
B4	20	600	3.3	181	2	300	30.00
B5	16	400	3.3	121	2	200	25.00

B6	20	200	3.3	60	2	100	10.00
B7	12	600	3.3	181	2	300	50.00
B8	12	400	3.3	121	2	200	33.33
B9	16	200	3.3	60	2	100	12.50

The third set of models is mainly designed to examine the effect of Ro/WC and Ro/WL parameters on wall behavior. In addition to the two mentioned parameters, the wall thickness is also subject to alteration in the samples. The change in thickness offers a more comprehensive perspective on the behavior of the wall.

Table 3: The parameters of the third set of software samples

	t(mm)	Ro(mm)	Ro/Wc	Wc(mm)	Ro/Wl	Wl(mm)	Ro/t
C1	20	250	2.5	100	2	125	12.50
C2	16	250	2.5	100	2	125	15.63
C3	12	250	2.5	100	2	125	20.83
C4	20	250	2	125	2	125	12.50
C5	16	250	2	125	2	125	15.63
C6	12	250	2	125	2	125	20.83
C7	20	250	3.3	75	1.5	166	12.50
C8	16	250	3.3	75	1.5	166	15.63
C9	12	250	3.3	75	1.5	166	20.83
C10	20	250	3.3	75	2.5	100	12.50
C11	16	250	3.3	75	2.5	100	15.63
C12	12	250	3.3	75	2.5	100	20.83
C13	20	250	3.3	75	3	83	12.50
C14	16	250	3.3	75	3	83	15.63
C15	12	250	3.3	75	3	83	20.83

Findings

Figures 5, 6, and 7 demonstrate the effect of different input parameters on the strength of RS-SPSWs. At constant ratios of Ro/Wc and Ro/Wl, the ratio of strength per ring increases sharply as the thickness rises. As the radius of the rings decreases, the increase in the strength of the shear wall results in an increase in the wall thickness with a slower slope. The figure shows that the slope for Ro=250mm is lower than that of Ro=400mm and 600mm (Figure 5).

The findings also indicate that at a fixed ring radius (Ro=250 mm) and fixed link width (Wl=12.5mm), changes in the Ro/t and Ro/Wc parameters alter the ratio of strength/ring. Furthermore, it can be seen that the increase of Ro/t and Ro/Wc parameters causes a strong increase in the ratio strength/ring in the steel plate shear wall. In simpler terms, in a fixed ring radius, increasing the ring width and increasing the thickness results in improved wall strength. The significant effect of ring width is visible in the strength of the steel plate shear wall (Figure 6).

Figure 7 illustrates the results for models with constant parameters of Ro=250mm and Ro/Wc=3.33 while the two parameters Ro/t and Ro/Wl are altered. The figure also clearly illustrates the increase in strength with the decrease in the Ro/t parameter which indicates that the increase in thickness stemming from altered ring radius and other parameters remaining constant causes a significant increase in the strength of steel plate shear wall. The findings on the changes in the Ro/Wl parameter are largely inconclusive, but in general, as the Ro/Wl increases, the strength decreases in the shear wall with a low slope, and hence, the decrease in the parameter of connection link leads to a relative decrease in the strength of the wall.

From the design point of view, the figures depicted in this section are highly informative to the design of steel plate shear walls with desired strength. Normally, high strength is achieved by using a thick sheet. Meanwhile, the biggest advantage of ring-shaped steel plate shear walls is that the strength of the wall can be increased or decreased by changing parameters other than the thickness of the plate. Also, in designing walls with low-level strength, parameters such as the width of the rings, the width of the connecting link, and the radius can be adjusted to optimal effect.

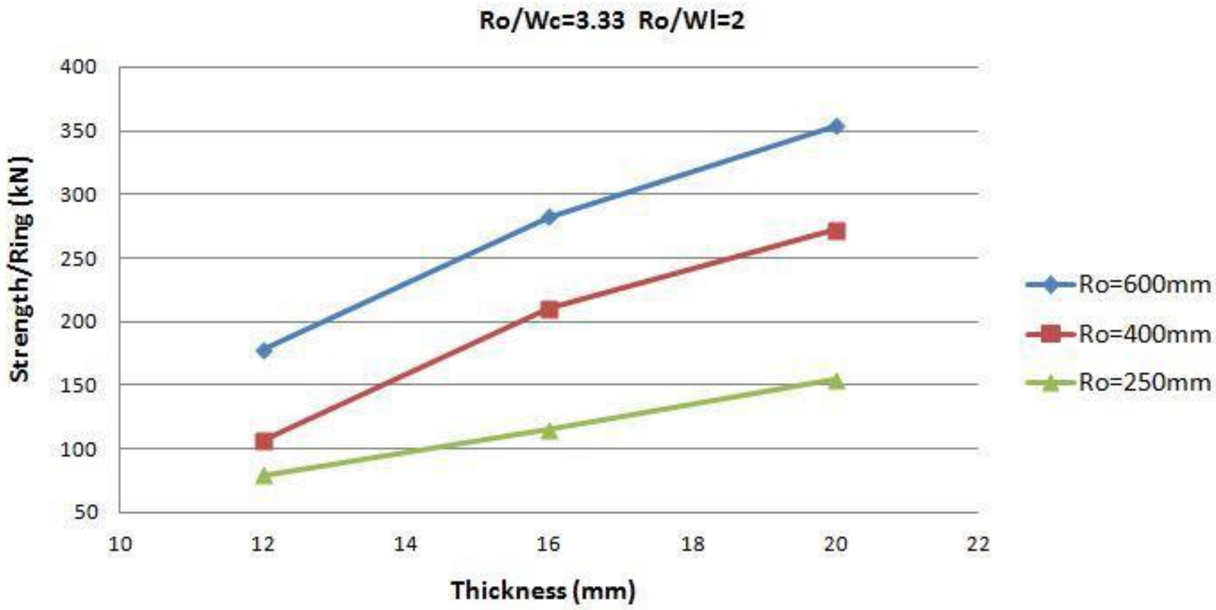

Figure 5: The effect of sheet thickness and ring radius on the ratio of strength per ring

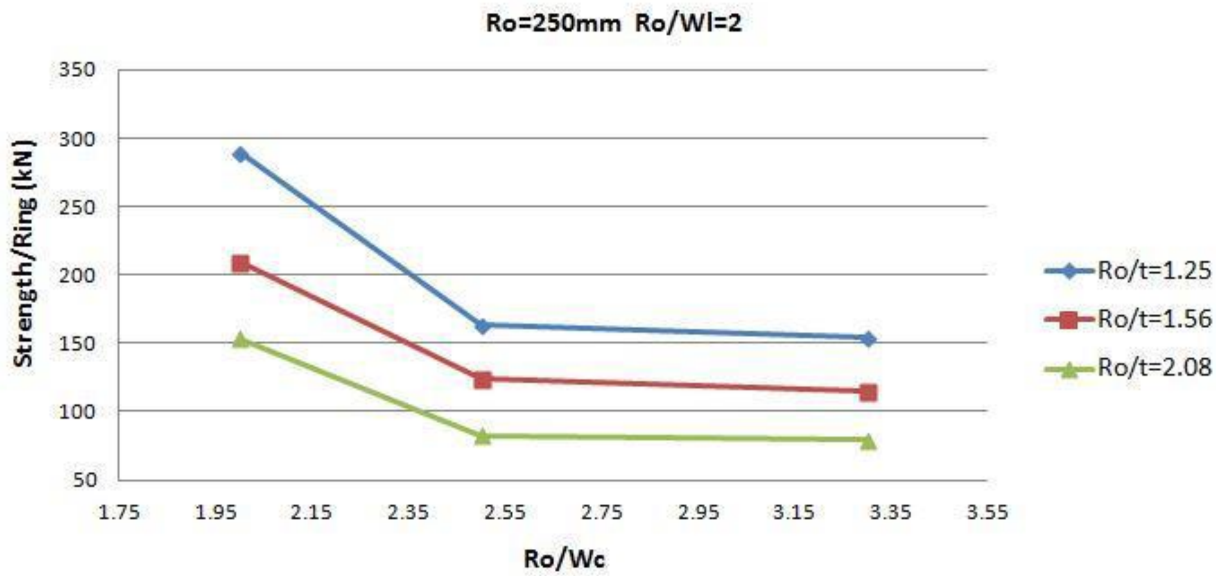

Figure 6: The effect of Ro/Wc and Ro/t on the strength and the ratio of strength per ring

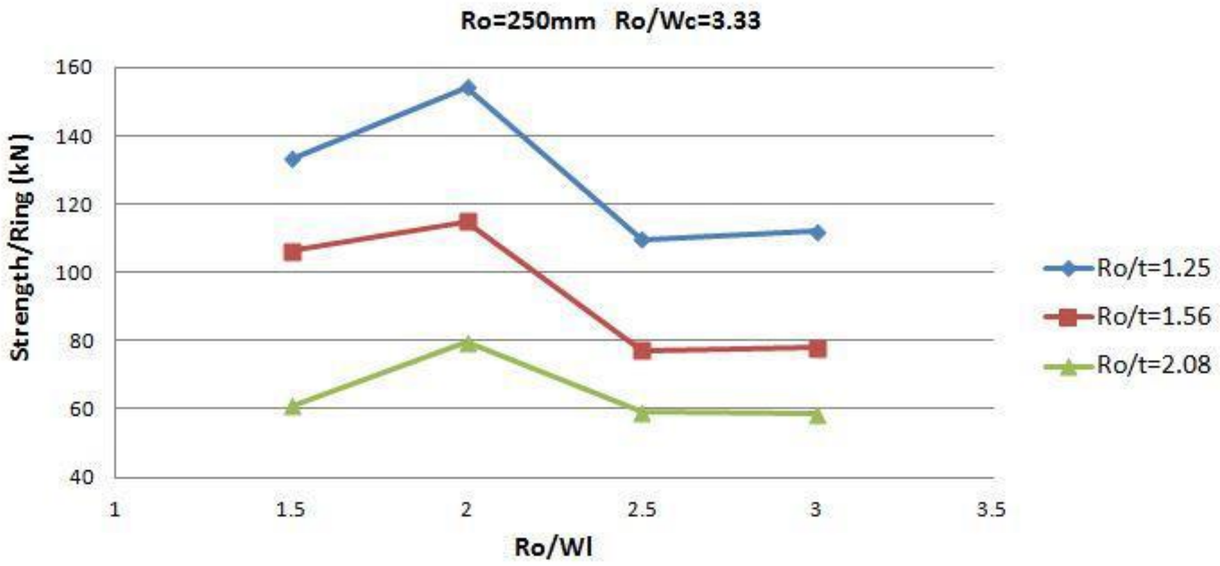

Figure 7: The effect of Ro/Wl and Ro/t on the strength and the ratio of strength per ring

Stiffness

Figures 8, 9, and 10 depict the effect of different parameters on the stiffness of RS-SPSWs. At constant Ro/Wc and Ro/Wl ratios, the stiffness per ring increases with the increase in the thickness of the metal shear wall sheet. For instance, at a fixed radius of Ro=400mm, an increase of 4mm in thickness leads to 129% in stiffness. These changes are less pronounced for smaller radii, and the changes in the thickness of the sheet do not have a significant effect on the ratio of stiffness to ring (Figure 8)

Furthermore, for a fixed ring radius (i.e., Ro=250mm) and a fixed ring width (i.e., Ro/Wl=3.33), both parameters of Ro/t and Ro/Wc greatly influence the ratio of stiffness per ring. For a given fixed ring radius, the increase of Ro/Wc value, and hence the decrease of ring width (Wc), the value stiffness/ring decreases. As such, increasing the width of the ring has a significant effect on increasing the stiffness of the wall (Figure 9).

According to the shape of the fixed ring radius (Ro=250mm) and fixed ring width (Ro/Wc=3.33), stiffness per ring in ring-shaped steel plate shear walls, generally by reducing the width of the connection link, is reduced This effect is reduced by reducing the thickness of the steel plate shear wall. A comparative analysis of the figures indicates that the change in the width of the ring has a more significant effect on the stiffness of the wall than the change in the width of the link. For instance, for Ro/t=1.56, with a decrease of 0.5 in Ro/Wc, the stiffness value of the wall decreases by about 63%, while decreasing the same value in Ro/Wl decreases the stiffness value by about 47% (Figure 10).

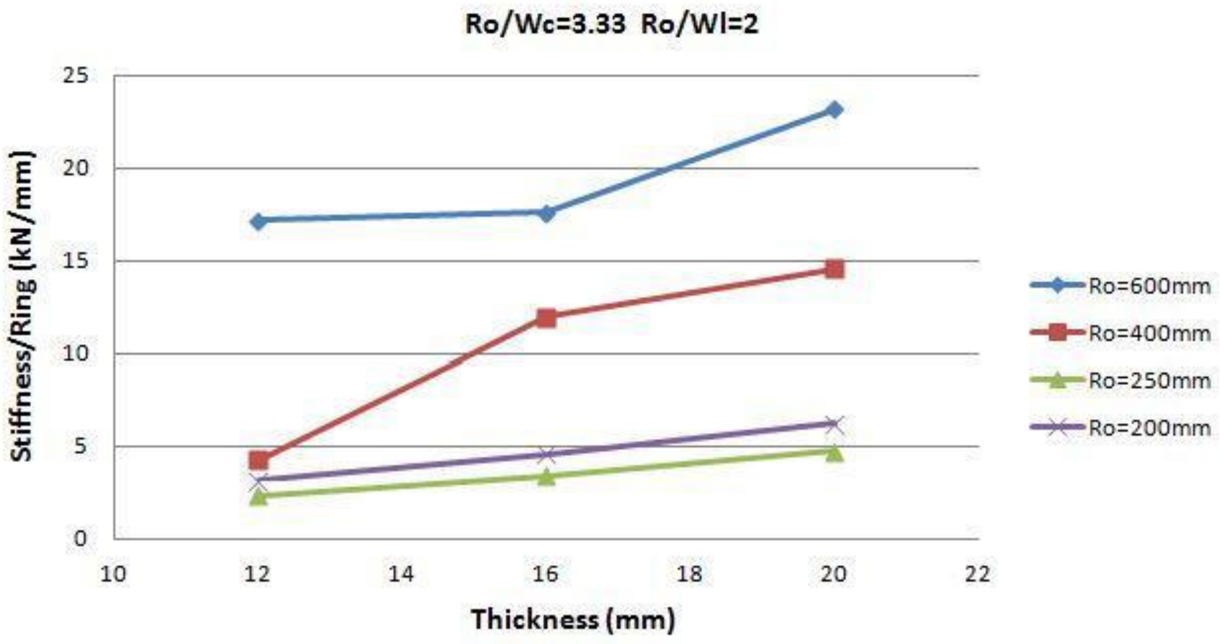

Figure 8: The effect of ring radius thickness on stiffness per ring

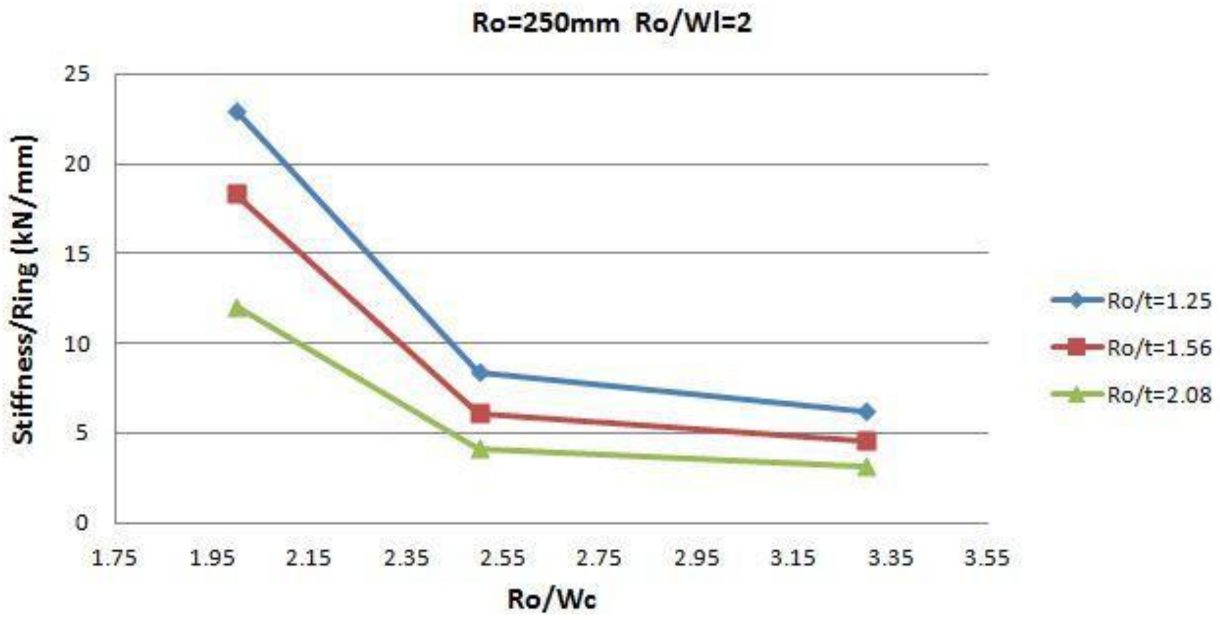

Figure 9: The effect of Ro/Wc and Ro/t on stiffness per ring

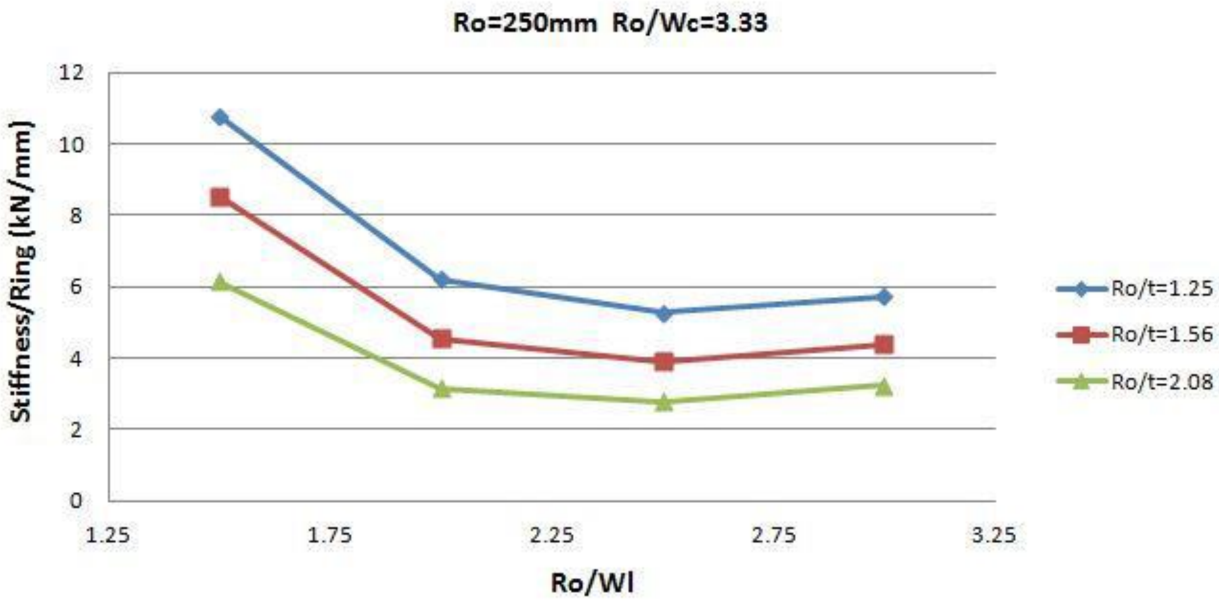

Figure 10: The effect of Ro/Wl and Ro/t on stiffness per ring

Conclusion

The thickness of the sheet proved to be a major indicator in all the behaviors of ring-shaped steel plate shear walls. A thinner sheet exhibited a more complete hysteresis behavior, in which the degradation of stiffness and strength is less pronounced, thereby increasing the dissipated energy. Thinner sheet experiences early buckling, leading to less energy dissipation. Also, the possibility of lateral torsional buckling is higher than general buckling in these samples. Ultimately, increasing the thickness increases the stiffness and strength of ring-shaped steel plate shear walls.

As expected, ring-shaped steel plate shear walls are highly sensitive to the diameter of the ring in the wall, which can be attributed to the altered type of wall buckling. The findings also suggested that the models with less ring radius exhibit more severe buckling, while the buckling in the walls with a larger radius is of the torsional lateral type. This change behavior of the wall leads to a change in the energy dissipation rate. Findings from hysteresis diagrams indicate that the torsional lateral buckling at larger radii results in the withering in the diagram. That is, this distinct type of buckling prevents the change of the shape of the ring from a circle to an elliptical, and hence ring-shaped steel plate shear walls work like a simple steel plate shear wall.

Also, the parametric results show that although the strength and stiffness per ring increase with the increase of the wall diameter, since walls with a smaller ring radius has more rings, the effect of the latter outweighs the former, and hence walls with smaller ring radius have greater strength and stiffness than that with a larger ring radius. It can be said that the only perceivable advantage of using a larger ring radius is to reduce the cost of cutting ring-shaped steel plate shear walls.

The idea behind this research is derived from the experiments conducted by Egrova et al. (2014), and hence the very first step in this research was to prove their laboratory results. Following the modelling stage, the first limitation the authors faced was that the results from Egrova et al. (2014) were not fully and comprehensively available, and only the final results were presented in that work.

Reviewing other studies in the current literature indicates that the behavior of steel plate shear wall in a one-span one-storied frame is very different from the behavior of these types of walls in multi-span or multi-storied frames. The same probable effect should also be examined for RS-SPSWs.

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