Calculating Dissipated Energy of Ring-Shaped Steel Plate Shear Wall

Farzad Zavari
M.S. Earthquake Engineering, Faculty of civil engineering, University of Tabriz, Tabriz, Iran

Abdolrahim Jalali *
Assistant Professor at Department of Structural Engineering, Faculty of Civil Engineering, University of Tabriz, Iran

Hassan Panahpour
Ph.D. student, Faculty of Civil Engineering, University of Tabriz, Tabriz, Iran.

Abstract- The goal of this study was to compute the dissipated energy of a ring-shaped steel plate shear wall. One of the parameters affecting the behavior of ring-shaped steel plate shear walls is the R_O/W_C ratio. Findings showed that changing the parameter from 2.2 to 3.3 demonstrated a more appropriate hysteretic behavior and a greater amount of dissipated energy, which was due to the increased possibility of lateral torsional buckling at the place where a ring was connected to a link. Compared to the previous parameter R_O/W_C, the parameter R_O/W_I was found to less affect the behavior of the ring-shaped steel plate shear wall. Increasing this parameter with a lesser slope resulted in reduced dissipated energy as well as reduced resistance and stiffness of the steel plate shear wall. This parameter did not have a significant effect on the dissipated energy percentage. The most important factor in designing this parameter was the congruence of this parameter with the previous one. In other words, the congruence of the ring's width and the connection link width was found to have a determining role in the behavior of the ring-shaped steel plate shear wall. The wall slenderness percentage (R_O/t & W_C/t) had a significant effect on the type of buckling in the steel plate shear wall. This made these parameters have greater effects on the dissipated energy and its percentage.

Keywords- ring-shaped steel plate shear wall, dissipated energy, type of buckling, plastic joints.

Introduction

A simple steel-plate shear wall is designed based on an ideal plate that endures the entire base shear. Also, consistent with a design force, in a steel plate shear wall design, the steel plate thickness is determined, with the lateral elements should be so designed to remain in the elastic area before the capacity of the tensile field in the plate maximizes.

To control early buckling and enhance stiffness, the plate thickness has to be increased. The increased thickness of the plate raises the tensile field, which is followed by the enhanced design force of lateral elements, consequently increasing the dimensions of lateral components, especially the columns. Studies have shown that a plate of 4.2 mm thick in a four-story building requires voluminous W399×36 columns. In addition, depending on the resistance required, a plate much less thick around 1.6 mm may be needed. Here, due to the limited minimum thickness required for the post-welding work, thicker plates are required (Berman, 2011).

In 1993, Elgaaly compared some specimens of steel plate shear walls with thin plates under cyclic loads and proposed an analytical specimen for the numerical computation of the walls' resistance. This analytical model could predict wall behavior under two welded and bolted plate states.

In 2000, Lubel et al. investigated experimental one- and multi-story specimens with an unstiffened steel plate shear wall under quasi-static cyclic loads. A four-story specimen and two single-story specimens were tested. Results indicated that the ductility of the upper and lower beams of the wall significantly contributed to preventing the creation of a plastic joint and out-of-plane deformation. Test data showed that the four-story structure was more ductile than the one-story structure due to the greater amount of overturning moments as a result of taller stories.

In 2000, Rezai et al. made a different analytical specimen and investigated it in Lubel's tested specimens.

In 2011, Berman et al. did a test on 6 specimens under cyclic loads. The goal of this test was to compare the cyclic behavior of steel plate shear walls with thin plates and braced frames. The goal was to design a shear wall with a braced frame to maintain the necessary lateral resistance and to be sufficiently light to be easily used in structures.

In 2005, Vian and Bruneau fabricated three experimental specimens: a panel with a solid plate (S2), a panel with 20 holes 200 mm in diameter (P),

and a panel with a quarter-circle portion in the upper part of a frame (CR). A plate of low-resistance steel was used along with a reduced beam section (RBS) were used in the upper and lower parts.
In 2011, Chen and Jhang studied the behavior of a steel plate shear wall with a low-resistance plate in one- and multi-story frames.
In 2008, Cortes and Liu conducted investigations into the behavior of steel plate shear walls with slits as a distinct lateral resisting system and tested three types of walls that may be used in structures. The specimens were made in a length-to-width (1:1) ratio. Also, the goal of designing these walls was to demonstrate their resistance against the entire base shear, not just cracks. In general, the panels tested by Hitaki and Matsui (2003) were similar to steel plate shear walls, though with different behaviors.
In 1990, Ciampi et al. tested a backup plate-connected butterfly-fused panel. The findings were compared to those of no-plate specimens.
In 1985, R.G. Tyler did a test on a dissipating instrument used by David Smith and Robert Henry in 1970. This instrument, known as the yielding frame, dissipated energy by the yielding of ring-shaped bars.
In 1990, Ciampi and Samuelli-Ferretti proposed some other dissipating energy instruments based on bending yielding. As stated above, these yielding frames were almost identical to the main system and were connected to tensile bracing systems. Under the cyclic lateral force, the frames yielded plastically while two braces on either side were under tension.
Tests by Egorova et al. (2014) demonstrated an idea of a steel plate shear wall as an effective way to control the steel plate shear wall buckling, reduce stiffness deterioration and resistance degradation, and increase the steel plate dissipated energy in the wall.
In sum, the goal of this study was to investigate new types of steel plate shear walls to reveal more dissipated energy by their special designs, without using bending connections, and to produce more reasonable lateral elements. A hysteresis diagram of these structural patterns was far balanced and solid, with stiffness deterioration and resistance degradation controlled under loading cycles.

Materials and Procedures

Initially, to measure the accuracy, efficiency, and validity of the modeling method and analyze software specimens, the laboratory specimens tested by Natalia Egrova (2014) were modeled and analyzed in ABAQUS software. This test used the hydraulic actuator (MTS Model 243.60) to apply force and deformation to the wall. This actuator was capable of applying a force of 650kN under pressure and a force of 1015kN under tension. The actuator applied the necessary shear deformation by its free end. The fixed end on the right side of the figure below is connected to the ground by steel bolts and creates rigid support conditions. The fabricated specimen was bolted by its four steel wings on either side between two sheets connected to lateral elements to create a state of clamping and to prevent any backlash during the test. It is noteworthy that the fixed lateral bases were welded by two braces to the base perpendicular to the sheet to prevent any base deformation perpendicular to the plane. As noted in Figure 1, the specimen is seen in a square shape with a length of 864 mm and a net length of 762 mm.

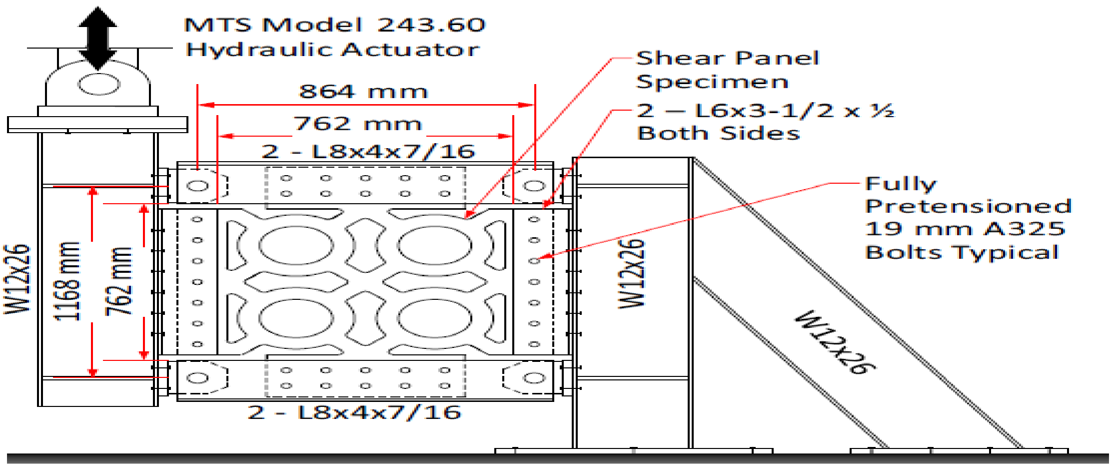

Figure 1: Schematic of the tested system (Egorova et al. 2014).

The loading protocol was obtained based on the ATC-24 Regulations. The shear deformation angle at the yield time (δy/a) was 0.5, with a value, which measured the plate length of the tested specimen, 864 mm.

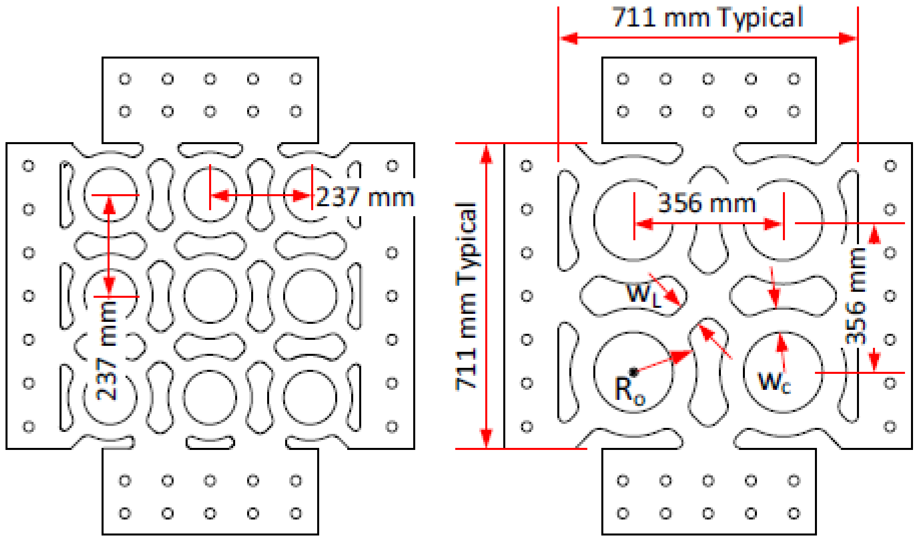

Figure 2: Schematic of laboratory specimens (Egorova et al. 2014).

The two parameters of R_O/t and W_C/t represented the slenderness of the ring and the parameter of a/t represented the overall slenderness of the wall, and they are considered as the general measures of the non-dimensional characteristics of ring-shaped steel plate shear wall.

Modeled Software Specimen Specifications

To investigate the pattern of ring-shaped steel plate shear walls in actual dimensions, samples of various features were designed. In this design, the goal was to examine the effects of wall properties such as ring diameter, the sheet thickness of the ring-shaped shear wall, the widths of the rings and connection links, etc. on stiffness and resistance.

Input Parameters

The Thickness of the Ring-shaped Steel Plate Shear Wall Sheet (t)

The thicknesses of the shear wall sheet were 12, 16, and 20 mm. These values were designed to involve a large spectrum. The specimens were compared to interpret the effects of thickness on the output of the specimens with fewer errors. Initial predictions indicated that changing thickness could make the wall thickness value vary between 500kN~2700Kn.

The Outer Radius of the Rings (R_O)

The outer radii of the rings used in the design were 200, 250, 400, and 600 mm. In designing the wall using the outer radius equaling the lower bound of this range, one should note that the shear length of the wall increases with the outer diameter getting smaller, suggesting the rising production costs of this type of wall. Specimens designed with the upper bound of 600 mm indicate which combination of the characteristics and specifications of the ring-shaped shear wall will strengthen the potentiality of lateral torsional buckling.

Widths of the Rings (W_C)

Changes in the widths of the rings used in wall designs took the ratio of the outer radii of the ring to the widths of the ring (R_O/W_C), which were applied to the specimen designs. This ratio (R_O/W_C) indicated the slenderness of the ring, as changes to this parameter could change the walls' buckling behavior. The ratios opted for in this study were 3.2, 2.5, and 3. These ratios in design were selected by considering two main issues. First, very wide rings did not easily enter the plastic ranges and could not yield, which decreased the dissipated energy amount and showed an appropriate cyclic behavior. Second, very thin rings caused the wall to experience early lateral torsional buckling, thus increasing the pinching effects in the hysteresis diagram of the wall. Both cases had a bad effect on the wall's behavior.

Widths of Connection Links (W_I)

The parameter of the connection link width is expected to affect the plastic axial deformation of connection links. The plastic axial deformation affects the pinching value of the wall's cyclic behavior. This parameter has also been applied to the ratio of the outer radius of the ring to the connection link width (R_O/W_I), introduced in the specimen designs. The lower bound of this range was opted for because the width of the thin connection link could reach the plastic area earlier and experience a yield.

Output Parameters

The energy dissipated in the steel plate shear wall is produced by the yielding and creation of plastic joints in the ring and a connection system. Deformation makes the rings elliptical and because of this deformation, since the geometric form of the ring causes its transversal deformation to be equal to its longitudinal deformation, the wall will experience no early out-of-plane buckling, with the wall being more capable of dissipating energy. In sum, the energy dissipated by every ring will accumulate and demonstrate the total dissipated energy in the force-displacement diagram resulting from the cyclic loading (hysteresis).

Now, to measure the total dissipated energy amount, as suggested by the previous explanations, the hysteresis diagram of each of the specimens was obtained, and then the points obtained were implemented in Excel software and the diagram was illustrated by exact points. Later, the internal area value of the last hysteretic cycle was calculated in this software. To measure the area inside the curve, simple mathematical rules were used. Figure 3 below gives a schematic of the intended area.

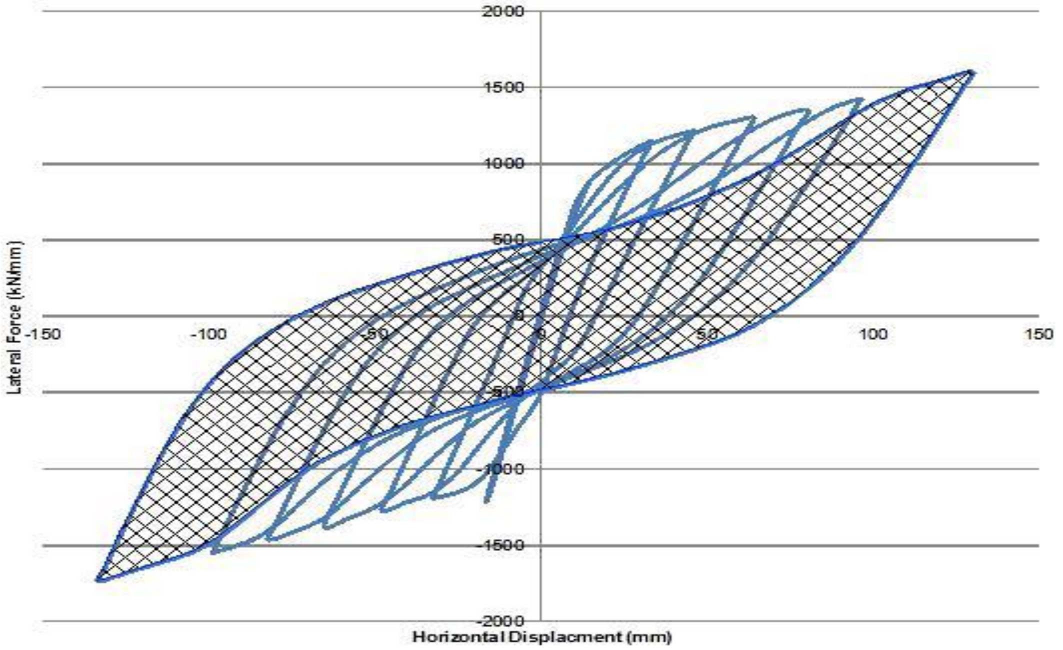

Figure 3: Calculation of total dissipated energy

Ratio of Dissipated Energy

The ratio of energy dissipated is a comparison of a designed specimen and an ideal specimen. This ratio indicates to what extent the energy dissipated by a ring-shaped steel plate shear wall is close to the energy dissipated by an ideal steel plate shear wall system with the same dimensions and features. This ideal system occurs when no pinching or resistance drop occurs in the wall. Therefore, the higher the ratio of energy dissipated, the more capable and effective the wall will be in dissipating energy.

To calculate this ratio, a displacement-force diagram under cyclic loading is illustrated for each specimen. Then, a parallelogram is drawn on the diagram, which dominates the entire hysteresis diagram. Its horizontally inclined sides are drawn from the highest and the lowest points in the diagram, with a slope equal to the lowest slope (the most horizontal tangent over the diagram) of a tangent line over the last cycle of the hysteresis diagram. Similarly, its vertically inclined sides, as in the previous method, are drawn from the endmost point on the right and left sides of the diagram, with a slope equal to the highest tangent line slope (the most vertical tangent over the diagram) over the last cycle of the hysteresis diagram. The intersection of the upper and lower lines and the two right and left lines produces a parallelogram. Now, the area inside the diagram equals the amount of energy dissipated by an ideal system. The ratio of the total energy dissipated, examined and obtained in the previous section, to the amount of energy dissipated by the ideal system was estimated and led to the ratio of the energy dissipated. The schematic of the way this parallelogram was obtained is given below.

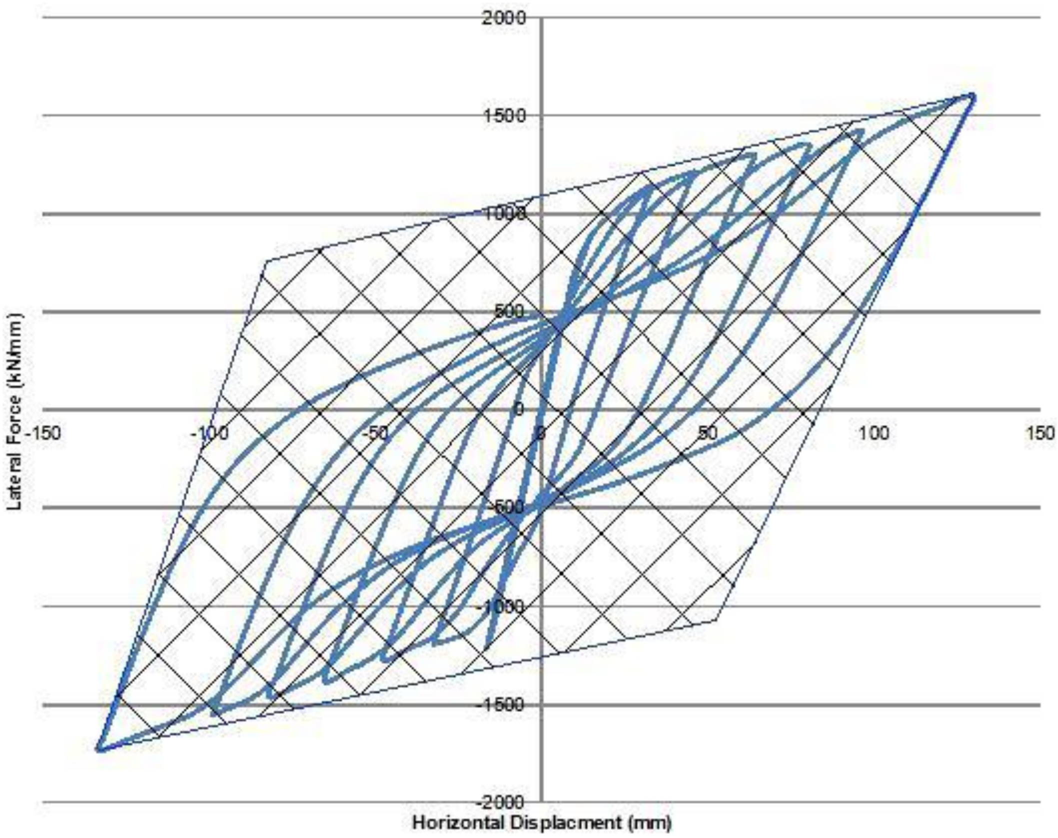

Figure 4: Calculation of the energy dissipated by the ideal system

Set of Software Models

This section summarily concerns all specimens designed and modeled in the software. Software specimens are mostly designed to investigate the effects of wall thickness. According to specimen characteristics, it was clear that the parameters were constant in the three specimens with only the thickness parameter experiencing a change.

Table 1: First group of software specimens

	t (mm)	R_O (mm)	R_O/W_C	W_C (mm)	R_O/W_L	W_L (mm)	R_O/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 software specimens were mainly designed to investigate the effects of the outer radius of the ring (R_O). In the table specimens, the two parameters of R_O/W_L and R_O/W_C were assumed to be constant in all specimens, with other values changing with the change of R_O and t. Because the outer diameter and thickness are two key and influential parameters, they include various values.

Table 2: Second group of software specimens

	t (mm)	R_O (mm)	R_O/W_C	W_C (mm)	R_O/W_L	W_L (mm)	R_O/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 following software specimens are mainly designed to investigate the effects of R_O/W_C and R_O/W_L parameters on the wall's behavior. In addition to the two parameters, the wall's thickness was also seen changing in the specimens. A change in the thickness gives comprehensive insight.

Table 3: Third group of software specimens

	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

According to the figure, at constant R_O/W_C and R_O/W_I ratios, the amount of energy dissipated increased with the increase of the thickness of the steel plate shear wall. This increase experienced a sharp slope with the changing thickness. At R_O=400 mm, an increase of 8 mm in the thickness increased the energy dissipated by around 3.5 times. This increase occurred because with the increased thickness of the wall, buckling in the sheet was delayed, which thus improved the wall's hysteretic behavior (Figure 5).

According to the figure, at a constant ring-shaped radius (R_O=250 mm) and a constant link width

(R_0/W_I=2), the energy dissipated decreased with the increase of the parameter of R_0/W_C, i.e., when the ring's width decreased. In other words, the increased width of the ring led to a significant rise in the amount of energy dissipated in the wall; for example, a 50 mm increase in the ring's width led to the dissipation of energy by 3.5 times (Figure 6).

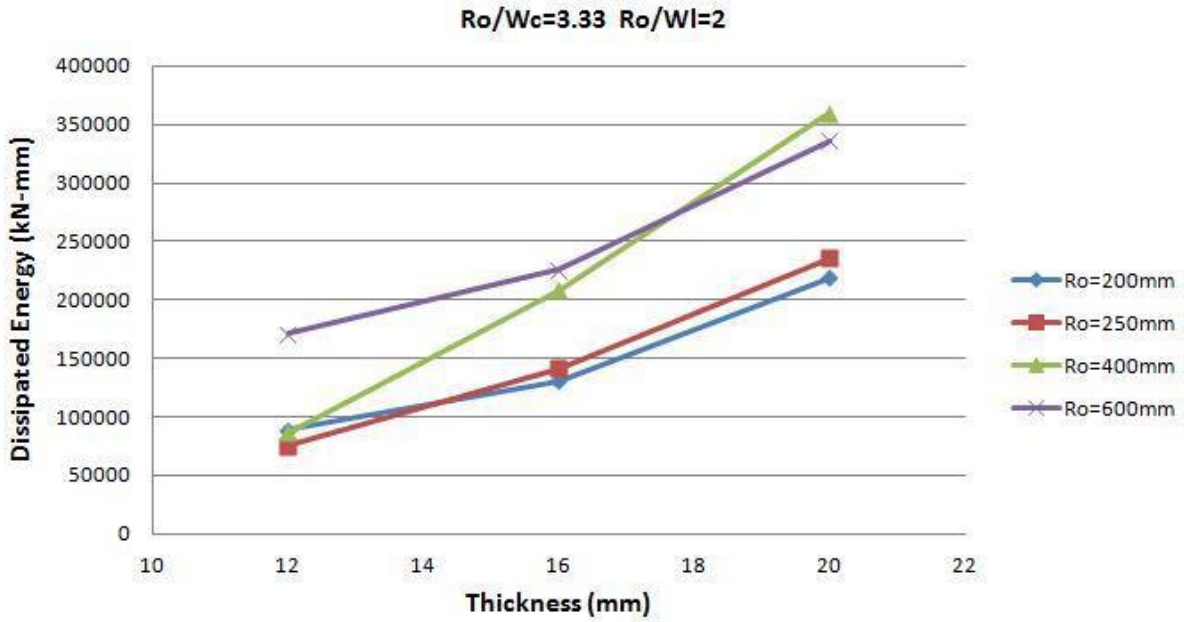

Figure 5: Effects of thickness and ring's radius on the energy dissipated

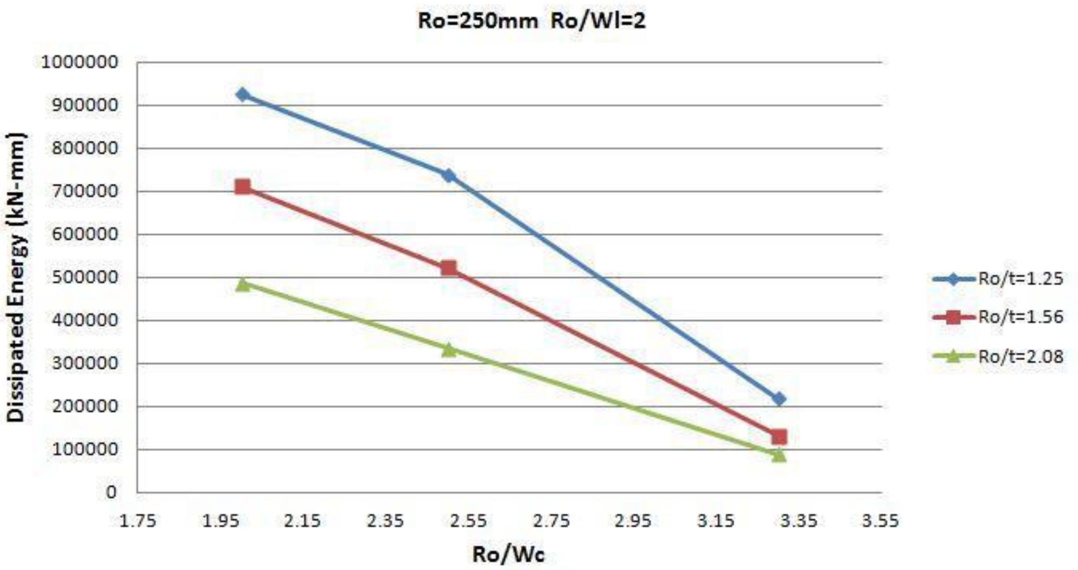

Figure 6: Effects of R_0/W_C and R_0/t on the dissipated energy

Percentage of Energy Dissipated

Figures 7, 8, and 9 illustrate the effects of various parameters on the energy dissipated. At constant R_0/W_C and R_0/W_I ratios, when the thickness of the steel plate shear wall increases, the percentage of the energy dissipated will rise. This indicates that slender shear walls tend to experience overall buckling in the walls. Shear walls with thicker sheets buckle late and have their dissipated energy closer to a perfect system. This is because, in shear walls with large-diameter rings, the possibility of buckling in the ring itself is greater than that in the entire sheet (overall buckling), which can reduce the energy dissipated. The diagram also illustrates that a diameter of 600 mm is lower than those of the other two diagrams (Figure 7).

A closer look at the figure reveals that at a radius of a ring with a constant ring-shaped width, the percentage of the dissipated energy increases with the decreased connection link width in the ring-shaped steel plate shear wall. In other words, as the connection link width decreases, the possibility of rings deforming from a circle into an ellipse would be more feasible, thus resulting in rings dissipating a greater amount of energy. It also increases the possibility of overall buckling compared to the possibility of lateral torsional buckling (Figure 8).

A closer look at the figure reveals that at a radius of a ring with a constant connection link width, the energy dissipated increases slightly with the decrease of the ring's width. The increased ring width slightly caused more energy dissipation. However, with the width not being in congruence with the connection link width and the ring's width getting larger than the connection link, the possibility of link buckling increases, resulting in the system withstanding local buckling. The greater congruence of the rings' widths with the connection links could increase the possibility of overall buckling while decreasing the lateral torsional buckling in the frame (Figure 9).

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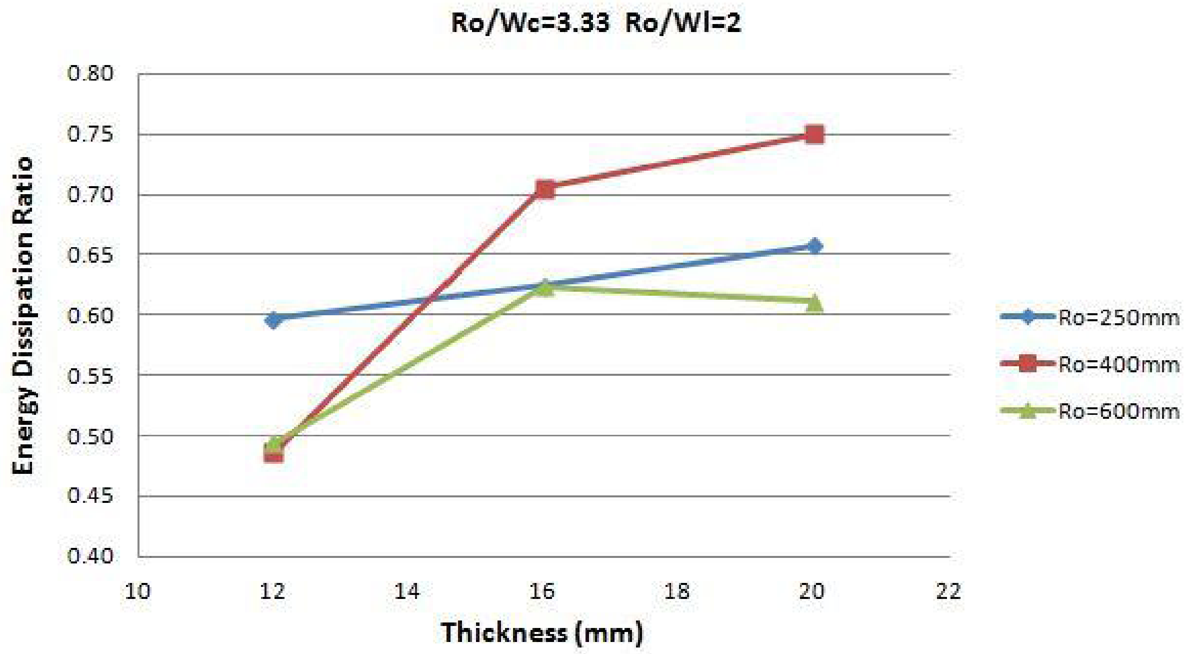

Figure 7: Effect of ring thickness and radius on the percentage of the energy dissipated

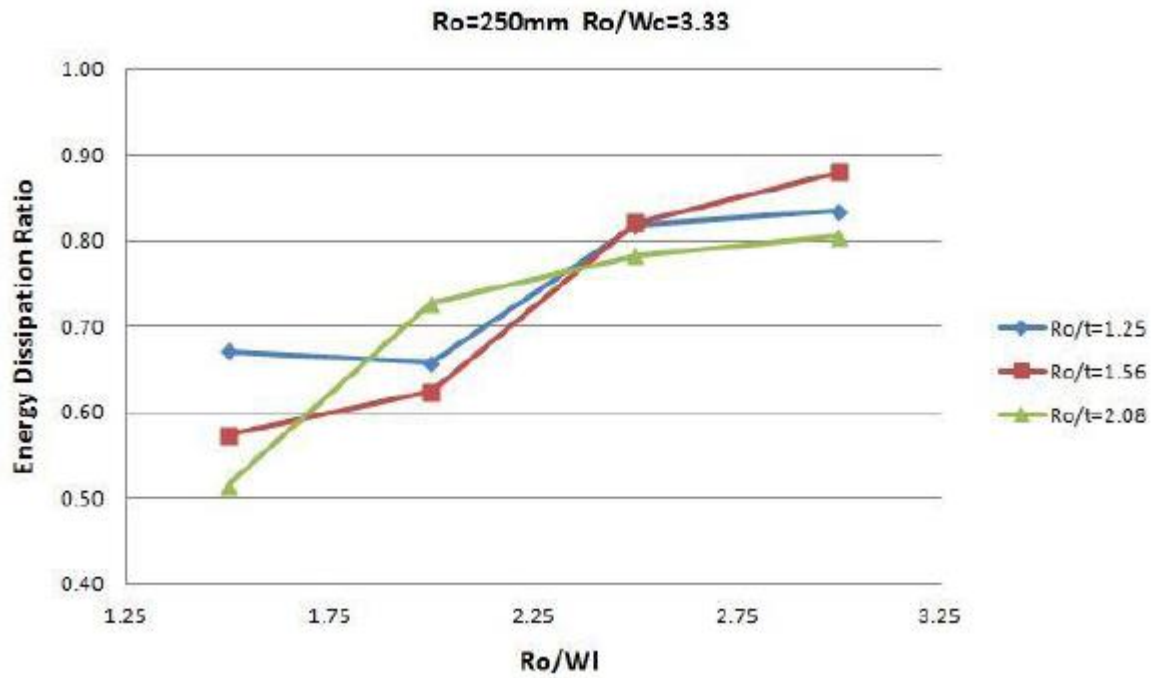

Figure 8: Effects of R_O/W_l and R_O/t on the percentage of energy dissipated

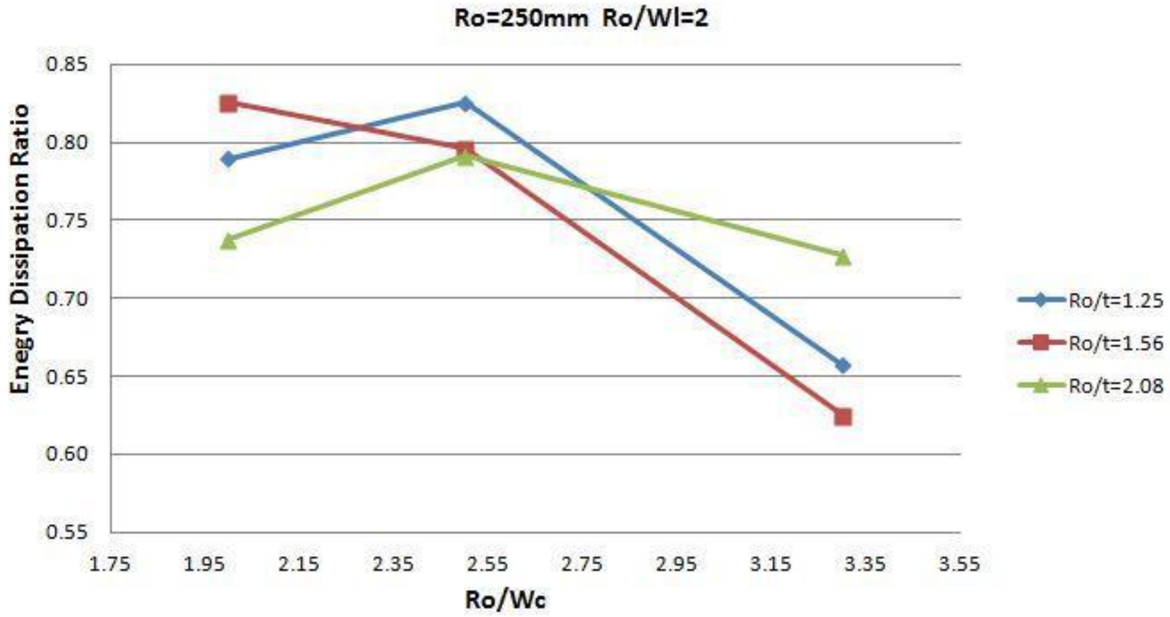

Figure 9: Effects of R_O/W_C and R_O/t on the percentage of energy dissipated

Conclusion

One of the parameters that affect the behavior of the ring-shaped steel plate shear walls is the R_O/W_C ratio value. Results indicated that the change of the parameter from 2.2 to 3.3 revealed a more appropriate hysteretic behavior and a greater amount of dissipated energy. As well, an increase in this parameter caused a sharp reduction in resistance and stiffens values, which was due to the increased possibility of lateral torsional buckling at the place where the ring was connected to the link.

The parameter R_O/W_I, compared to the previous parameter R_O/W_C, had a lesser effect on the behavior of the steel plate shear wall. Increasing this parameter with a slight slope reduced both the energy dissipated as well as the stiffness and resistance of the wall. This parameter, however, did not have much effect on the percentage of the energy dissipated. The most important factor in designing this parameter appeared to be its congruence with the previous one. In other words, the congruence between the ring width and the connection link width had a determining role in the behavior of the wall.

The slenderness percentage in the wall (R_O/t & W_C/t) had a significant effect on the type of buckling in the steel plate shear wall. This led to the greater effects of these parameters in the energy dissipated and the percentage of the energy dissipated.

The removal of pinching from the hysteresis diagram resulted in the ring-shaped steel plate wall revealing a greater amount of dissipated energy compared to the simple steel plate shear wall. Compared to the ideal hysteresis diagram, the percentage of the dissipated energy in the ring-shaped steel plate shear wall was around 22%, while this value for the simple steel plate shear wall was around 49%.

Concerning the amount of the dissipated force, the software specimens, designed in real dimensions, well indicated that the dissipated energy had increased considerably. With the calculation of the percentage of the dissipated energy, obtained from the ratio of the energy dissipated by the wall to the energy dissipated by the ideal system, the improvement in the energy dissipation was examined through numbers, and the values indicated the system was ideal. It is noteworthy that the percentage of the energy dissipated in the specimens averaged around 0.75, which produced an ideal result.

Problems that arose were the way cracks were created in the wall, their place of creation, and their expansion. Research in this regard enables more optimal designs and more resistant ring-shaped steel plate shear walls. Meanwhile, removing the problems helps delay the wall yielding limits by focusing on making its critical areas.

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