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SEISMIC BEHAVIOUR OF RING SHAPED STEEL PLATE SHEAR WALL

Simsha Suresh [1], Lekshmi L[2]

[1]M.Tech student, Structural Engineering and Construction Management, Vimal Jyothi Engineering College, Kannur, Kerala, India

[2]Assistant Professor, Civil Dept., Vimal Jyothi Engineering College, Kannur, Kerala, India

***Abstract*: Ring shaped - steel plate shear walls (RS-SPSWs) are a newly invented lateral load resisting system. It resists the buckling of the panel through the deformation properties of the rings. This paper is an attempt to develop a new RS-SPSW that has more strength, stiffness and energy dissipation. The configuration of cut-outs, thickness of steel plate, outer radius of the rings, width of the rings etc are selected as the input parameters for this study. In order to simulate the behaviour of RS-SPSW, a non linear static analysis was conducted by using ANSYS 14.5. Hysteretic curves, monotonic load displacement curves and out of plane displacement of plate are demonstrated. From the preliminary analysis of RS-SPSWs under different configuration of alignment of the rings, it is found that the steel plate shear wall panel with rings arranged along perimeter (RS-G-3) as well as completely aligned ring models (RS-G-2) shows promising results. While comparing RS-G-2 and RS-G-3, RS-G-3 has strength and stiffness about 10.82% and 48.11% than that of RS-G-2. Increase in plate thickness and width of the connecting ring as well as decrease in outer ring radius shows improvement in efficiency of both structures. Based on the different parametric analysis, it can be concluded that RS-G-3 shows better performance on the basis strength and stiffness. Conversely RS-G-2 shows more energy dissipation than that of RS-G-3.**

***Keywords*: Ring shaped steel plate shear wall, stiffness, energy dissipation, hysteresis loop.**

1. INTRODUCTION

Steel plate shear walls (SPSW) is an important lateral load resisting system. The use of these systems has been increased in the recent years due to research demonstrating SPSW behaviour and inclusion in U.S. building codes [3]. SPSW used not only in the high seismic areas, but also for wind and low seismic applications. A new type of steel plate shear wall (SPSW) had developed by Abhilasha maurya et al. in 2014, known as ring shaped steel plate shear wall (RS-SPSW). It can resist out-of-plane buckling and improved energy dissipation and stiffness [1]. The RS-SPSW concept exploits the deformation properties of a ring to mitigate buckling [5]. RS-SPSW consists of a SPSW in which the steel web plate is cut with a pattern of holes leaving ring-shaped portions of steel connected by diagonal links [5]. The ring shape resists out of plane buckling through the mechanics of how a circular ring deforms into an ellipse [5]. Because of the unique features of the ring's mode of distortion, the load-deformation response of the resulting RS-SPSW system can exhibit full hysteretic behavior [2]. Reduced buckling also leads to greatly improved stiffness. Improved energy dissipation and stiffness make the moment connections that are required for conventional SPSW unnecessary [1]. Furthermore, through the introduction of more design variables associated with the geometry of the rings, it is possible to separately tune the strength, stiffness, and ductility of the RS-SPSW system [2].

The objective of this paper is to study the seismic behavior of ring shaped steel plate shear wall (RS SPSW) by considering various input parameters like configuration of cut-outs, thickness of steel plate used, outer radius of the rings and width of the rings. In order to study the effect of these parameters 16 scaled down models are created in ANSYS software and subjected to cyclic loading. Compare measured strength, stiffness, energy dissipation, yielding displacement of different models and to explore the seismic behavior of RS-SPSW under different conditions.

1.1 Finite element model:

Finite element models using shell elements have been used in the past to model SPSW. Full wall behavior with good accuracy can show through these computational models. For this research, scaled down model of the RS-SPSW of size 861mmx861 mm panels are selected. Models are drawn by using CATIA V5R20. Finite element analysis is done by using ANSYS 14.5. Analysis is based on non linear static analysis. Nonlinear geometric effects associated with large deflection are considered in this analysis. Generalized shell elements 3D 4 nodded 181 are used as plate element. Boundary element consists of I sections all around the panel. It is modelled by using solid 10 nodes 187 element. Typical finite element model of the RS-SPSW system with shell and solid elements are shown in figure 1. Table 1 shows the modelling details.

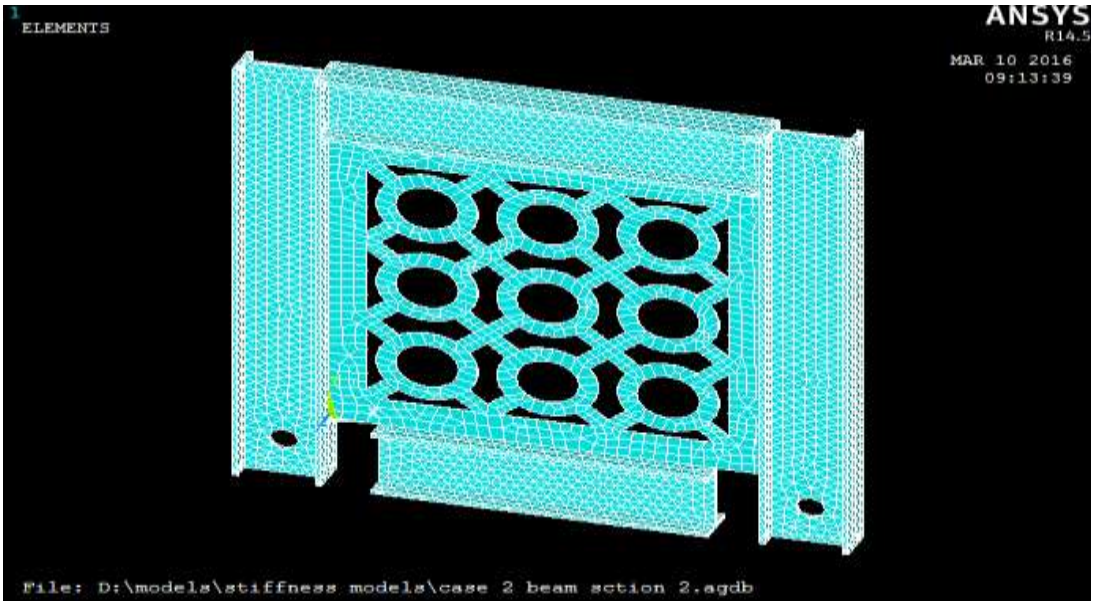

Figure 1: Typical finite element model of the RS-SPSW system with shell and solid element

Table 1: Modelling details

Parameter 1	Parameter 2	Parameter3	Parameter4
RS-G-2	RS-G-2-t 6.4	RS-G-2-Ro 75	RS-G-2-Wl 25
RS-G-3	RS-G-2-t 9.5	RS-G-2-Ro 100	RS-G-2-Wl 45
RS-G-4	RS-G-2-t 12.7	RS-G-3-Ro 75	RS-G-3-Wl 25
RS-G-5	RS-G-3-t 6.4	RS-G-3-Ro 100	RS-G-3-Wl 45
-	RS-G-3-t 9.5	-	-
-	RS-G-3-t 12.7	-	-

RS-G = ring shaped, geometry, t = Plate thickness, Ro = outer ring radius, Wl = Width of the link.

Parameter 1-Different geometry(G),Parameter 2- thickness of plate(t), Parameter 3- outer ring radius(Ro), Parameter 4- width of the connecting link(Wl).

1.2 Material properties:

Material properties are based on the test which was conducted in Virginia Tech, Blacksburg (2014) [1]. And those properties are summarised in Table 2. A 36 steel is used for both plate and boundary elements. Poison's ratio as 0.3 and nonlinear kinematic hardening is chosen for analyisis.

Table 2: Material properties (Source: *ASCE, 103, 179– 189)*

Plate thickness (mm)	Modulus of elasticity (GPa)	Yield strength (MPa)
12.7	210	331
1.9	200	296
6.4	210	317
9.5	203	296

1.3 Boundary conditions:

The boundary conditions are provided by considering the boundary condition of a full wall. The top horizontal and the two vertical boundary elements connections are provided as pinned. The base of the vertical boundary elements are fixed against all degree of freedom except Z axis rotation. All degree of freedom are fixed at the bottom horizontal boundary elements (VBE). I section at the bottom are removed with a length of 110mm from both face of the VBE to prevent local buckling at corners.

The load and deflection history are selected on the basis of ATC-24 protocol [4]. This document states that its purpose is to provide guidance in the selection of loading histories and the presentation of results for slow cyclic loading [4]. The load deflection history of steel is shown in figure 2. The displacement is applied in both +ve and -ve direction along the X axis, which is provided on the nodes in the top flange of the boundary element. The models are analysed for cyclic displacement response. The target displacements, number of cycles, and shear distortion for each displacement level is given in Table 3.

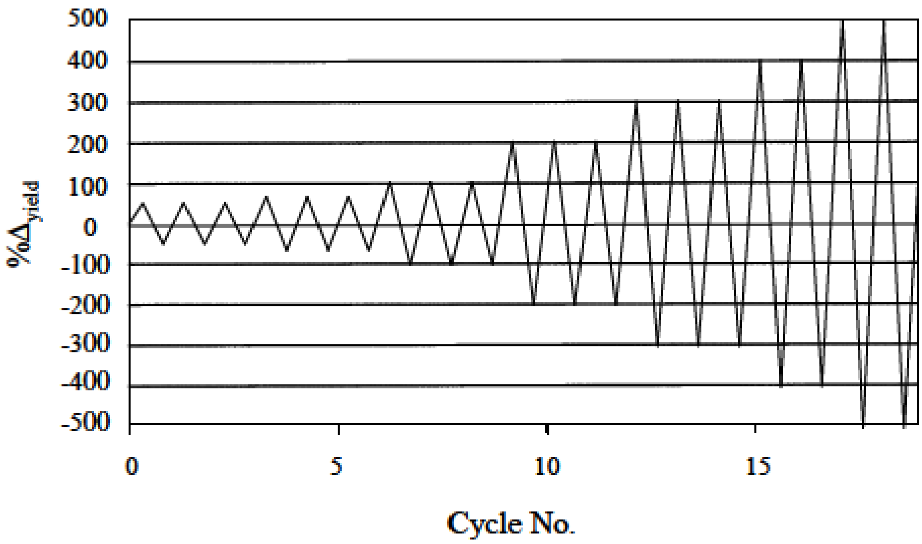

Figure 2: Steel - ATC-24 (ATC-24, 1992) (Source: *ASCE, 103, 179– 189)*

Table 3: Displacement protocol (Source: *ASCE, 103, 179– 189)*

Level	**Target shear distortion angle, δ/a, %**	**Target shear displacement, δ (mm)**
1	0.25	2.15
2	0.37	3.18
3	0.5	4.305
4	1	8.61
5	1.5	12.915
6	2	17.22
7	2.5	21.525
8	3	25.83

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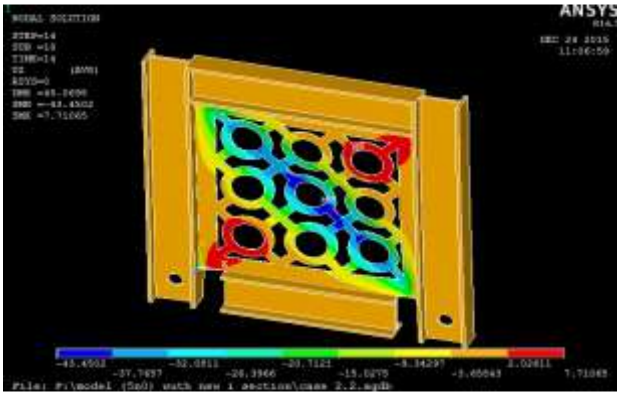
2. RESULTS AND DISCUSSIONS OF PARAMETER AFFECTING THE BEHAVIOUR OF RS-SPSW

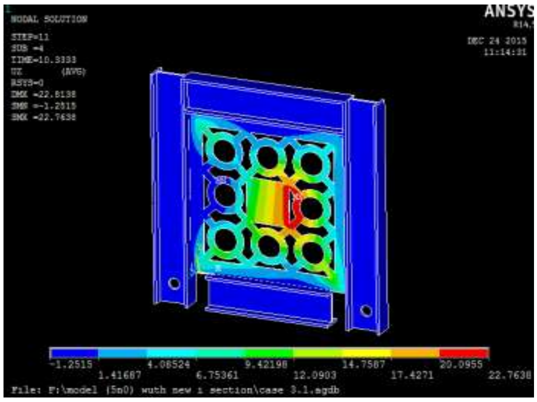
First, several key parameters affecting the overall behavior of the RS-SW system such as geometrical arrangement of ring units ,steel plate thickness, outer ring radius, width of the links are identified. Then, through detail finite element analyses, the influence of each parameter on the behavior of the system is investigated as follows.

2.1 different geometrical arrangements:

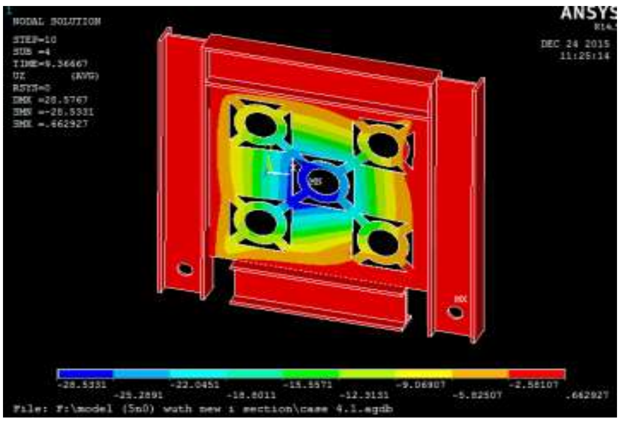
Four different patterns of ring arrangements are considered to explore the characteristics of RS-SPSW. Scaled down models of 861x861x 6.4mm size plates are considered. The number of rings per panel is changed in accordance with their geometry, which is sown in figure 3. Australian I section U200x46 are used as boundary elements.



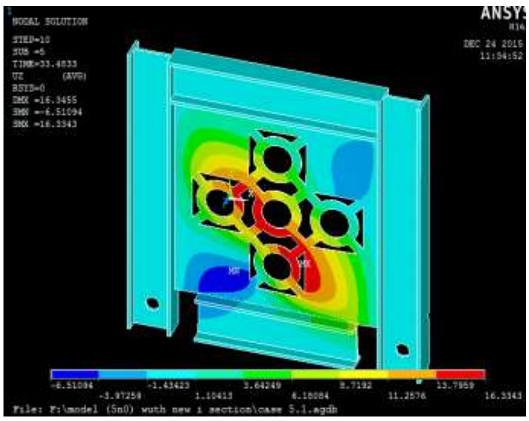
RS- G-2



RS- G-3



RS- G-4



RS- G-5

Figure 3: Comparison of out of plane displacements

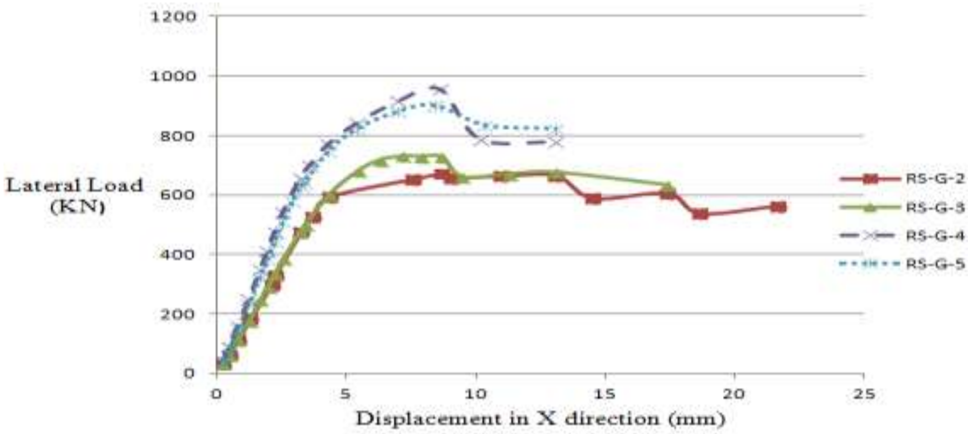


Figure 4: Comparison of hysteresis loop of different plate geometry

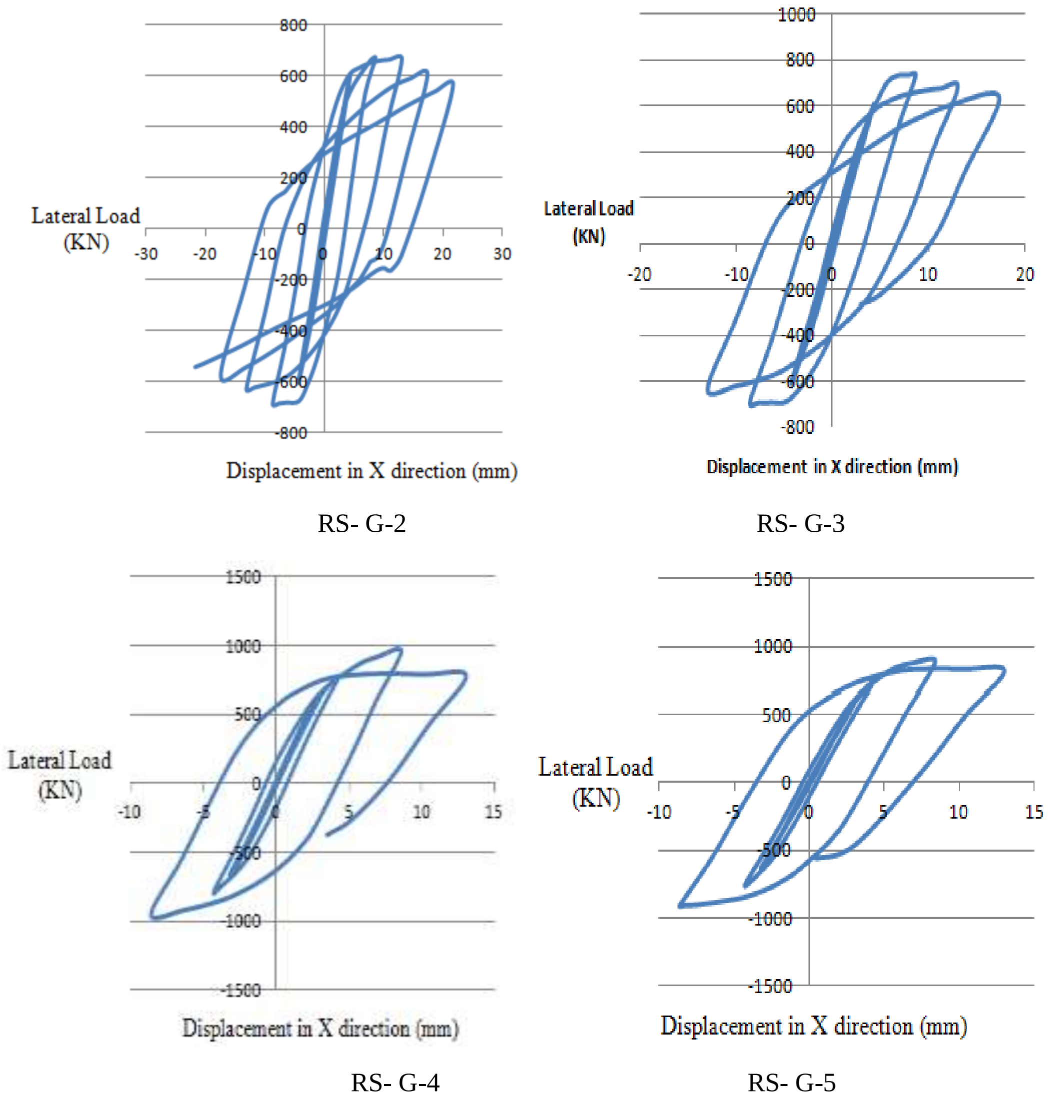


Figure 5: Comparison of hysteresis loop of different plate geometry

Table 4: analysis results of different plate geometry

Model	Strength (kN)	Yielding displacement (mm)	Peak strength (kN)	Stiffness (kN/mm)
RS-G-2	649.49	5.01	671.78	59.02
RS-G-3	719.84	6.27	731	87.41
RS-G-4	772.34	4.3	954.86	132.007
RS-G-5	748.25	4.3	901.07	131.33

RS-G-2 is capable of developing plastic hinges on the rings. Maximum yielding of the plate occurred along the diagonally. It can provide nearly full hysteretic behavior and energy dissipation. While comparing all models, RS-G-2 shows better seismic performance than other. From the figure 4, it is clear that RS-G2 has more energy dissipation than that of other models. On the other hand RS-G-3 has more strength, stiffness and yielding displacement than that of RS-G-2. The increment of strength, stiffness and yielding displacement are in the order of 70.35KN, 28.39KN/mm and 1.23mm respectively. The comparisons of out parameters are given in table 5.

The output parameters of RS-G-4 and RS-G-5 are comparable. But brittle failure is observed at early stage itself. From the monotonic load displacement graph shown in figure 4, it is clear that, among all models RS-G-2 and RS-G-3 shows more energy dissipation and ductility property.

2.2 Analysis of RS-SPSW based on plate thickness:

RS-G-2 and RS-G-3 are analyzed based on different plate thickness, such as 6.4mm, 9.5mm, and 12.7mm. All other parameters are kept constant. As same as previous section 3.1 and here also Australian I section U200x46 was used as boundary elements.

Table 5: analysis results of different plate thickness

Models	Streng-th (kN)	Yielding displace-ment (mm)	Peak streng-th (kN)	Stiffness (kN/mm)
RS-G-2-t 6.4	649.49	5.01	671.78	59.02
RS-G-2-t 9.5	815.04	7.02	1004.4	85.57
RS-G-2-t 12.7	904.68	7.13	1030.1	96.87
RS-G-3-t 6.4	719.84	6.27	731	87.41
RS-G-3-t 9.5	821.31	8.64	1008.5	94.12
RS-G-3-t 12.7	1036.9	8.62	1062	108.2

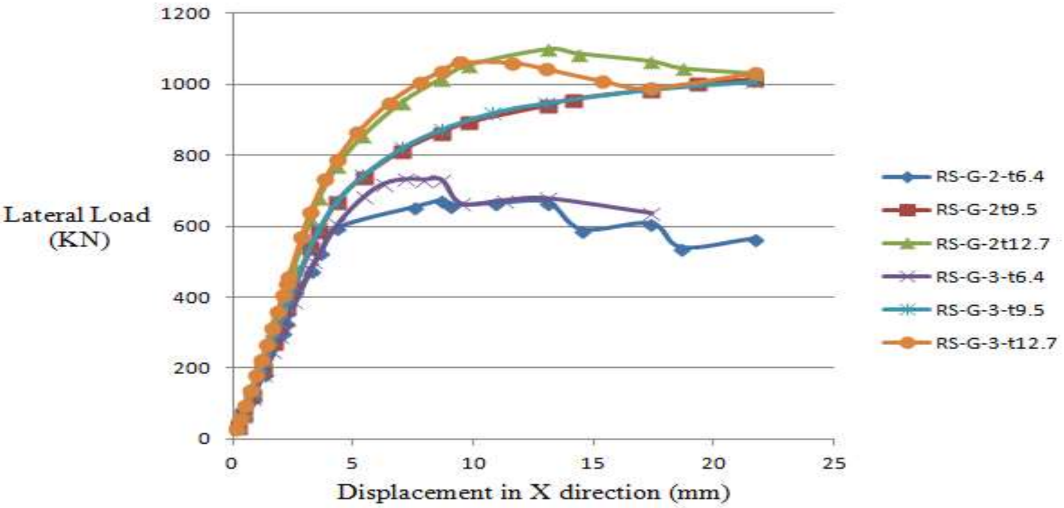
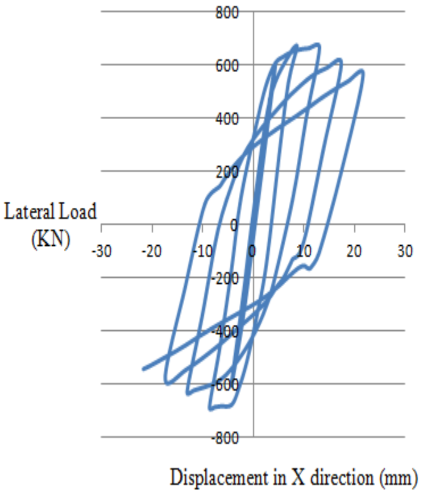
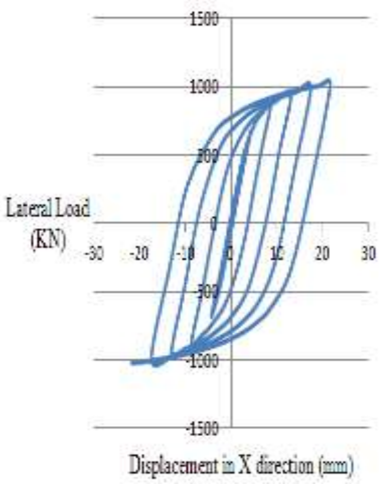


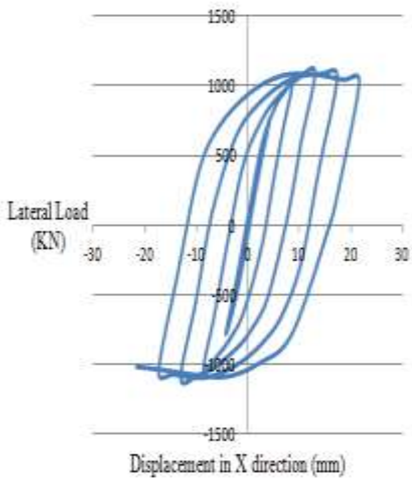
Figure 6: Comparison of monotonic load - displacement graph of different plate thickness



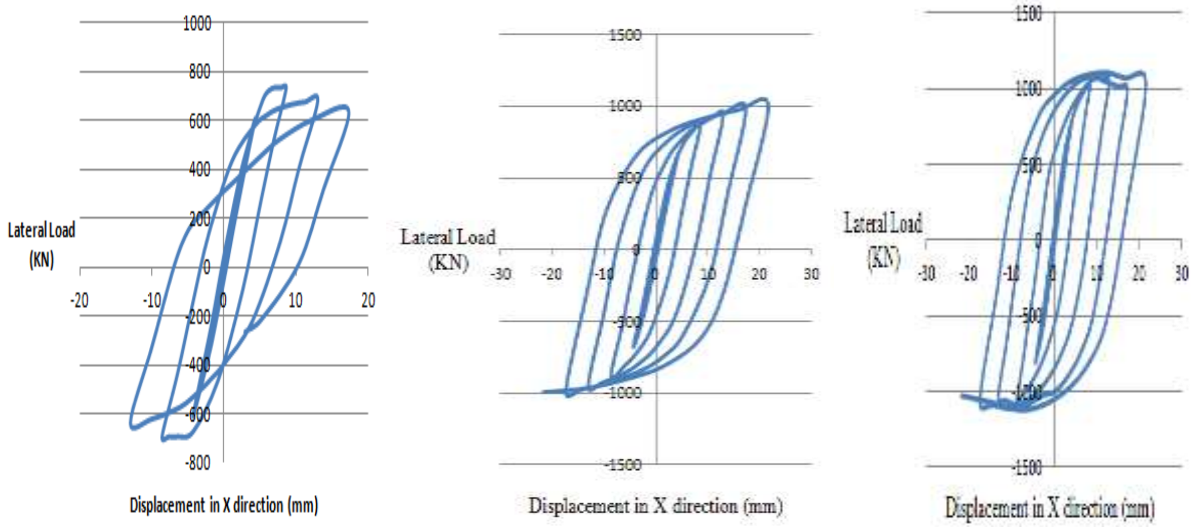
RS- G-2- t6.4



RS- G-2- t9.5



RS- G-2- t12.7



RS- G-3- t6.4 RS- G-3- t9.5 RS- G-3- t12.7

Figure 7: Comparison of hysteresis loop of different plate thickness

From the figure 7, it was observed that RS-G-2 with thinnest web plate suffered a reduction in stiffness of about 58.28% in the last cycle as compared to the first cycle. While comparing with RS-G-2-t 9.5, the decrease in stiffness is found to be comparatively less. The RS-G-3-t 6.4 suffered a reduction in stiffness around 52.28% in the last cycle than that of first cycle. While compared RS-G-2-t 6.4 and RS-G-3-t 6.4, it is found that RS-G-2-t 6.4 suffered more reduction in stiffness than that of RS-G-3-t 6.4.

From the table 5 it was cleared that, RS-G-3 has higher strength and stiffness than that of RS-G-2. The strength of RS-G-3-t 6.4 is around 70.35KN more than that of RS-G-2-t 6.4. Similarly, the strength of RS-G-3-t 9.5 is around 6.27KN more than that of RS-G-2-t 9.5. On the other hand RS-G-2 has more energy dissipation than that of RS-G-3. From the figure 6 it is clear that, plastic hinges are formed in 6.4mm thick plates. For higher thick plates the yielding of the ring as well as plastic hinges are not observed.

From this analysis it was clear that, the thickness of the web plate plays an important role in all the behavioral aspects of RS-SPSW. The thicker plate exhibits relatively full hysteretic behavior and does not experience substantial strength and stiffness reduction. This results in relatively much larger energy dissipation.

2.3 Analysis of RS-SPSW on the basis on outer ring radius:

The radius of the rings is selected as 85mm and 100mm for both cases (RS-G-2 and RS-G-3). Th**e** plate thickness, width of link and connecting ring provided as 6.4mm and 37.3mm and 37.3mm for all models. Australian I section U180x22 is used as boundary elements.

Table: 6 Comparison of analysis results of different outer ring radius

Model	Strength (kN)	Yielding displacement (mm)	Peak strength (kN)	Stiffness (kN/mm)
RS-G-2-Ro 85	668.21	5.38	860.75	89.04
RS-G-2-Ro 100	584.73	5.42	647.9	60.86
RS-G-3-Ro 85	678.46	4.875	845.46	106.79
RS-G-3-Ro 100	620.4	5.41	688.11	61.82

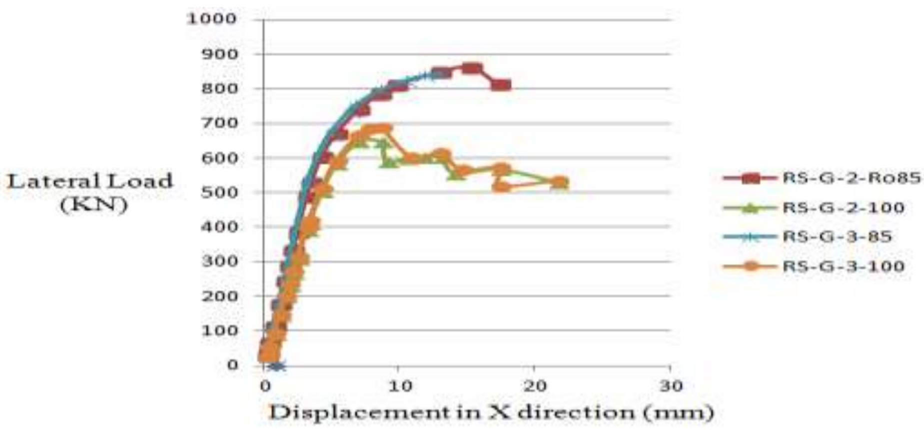


Figure 8: Comparison of monotonic load - displacement graph of different outer ring radius

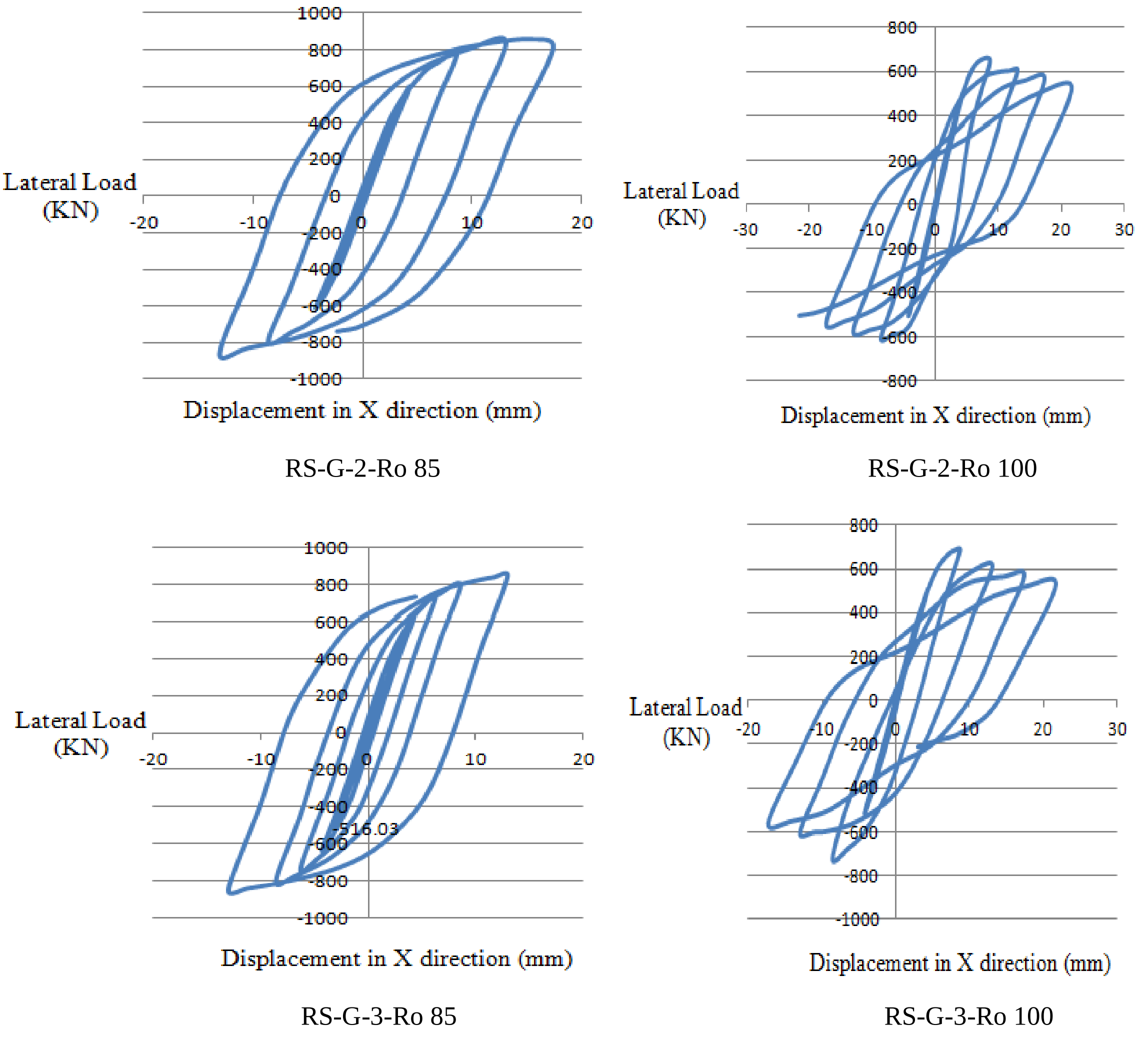


Figure 9: Comparison of hysteresis loop of different outer ring radius

The dependence of the hysteretic behavior on the ring radius is investigated in RS-G-2 and RS-G-3. From figure 9, it is found that the decrease in the outer ring radius will increase the energy dissipation capacity. While comparing all hysteresis loops it is observed that, the panel behaved as a stiff plate in the initial load cycles. As the load increases, the steel plate shear wall gets yielded and gradually decrease the strength and stiffness.

While comparing stiffness, RS-G-2-Ro 85 has increase in stiffness about 35.1% than that of RS-G-2-Ro100. Similar trend is also observed in strength and peak strength also. Conversely yielding displacement is more for RS-G-2-Ro100 than that of RS-G-2-Ro85.

From the table 6, it is observed that strength, stiffness and peak strength of RS-G-3 Ro 100 has 6.03%, 1.57% and 6.2% than that of RS-G-2 Ro 100. While comparing monotonic load displacement graph of models in figure 9, strength, stiffness and yielding displacement is more for RS-G-3. But energy dissipation is slightly higher for RS-G-2.

2.4 Analysis of RS-SPSW based on width of connecting link:

In order to study the effect of width of the connecting links, two widths are selected such as 25mm and 45mm for both cases. Outer ring radius, width of connecting ring, and plate thickness are provided as 100mm, 37.3mm and 6.4mm respectively for each case. Australian I section U200x46 is used for boundary elements.

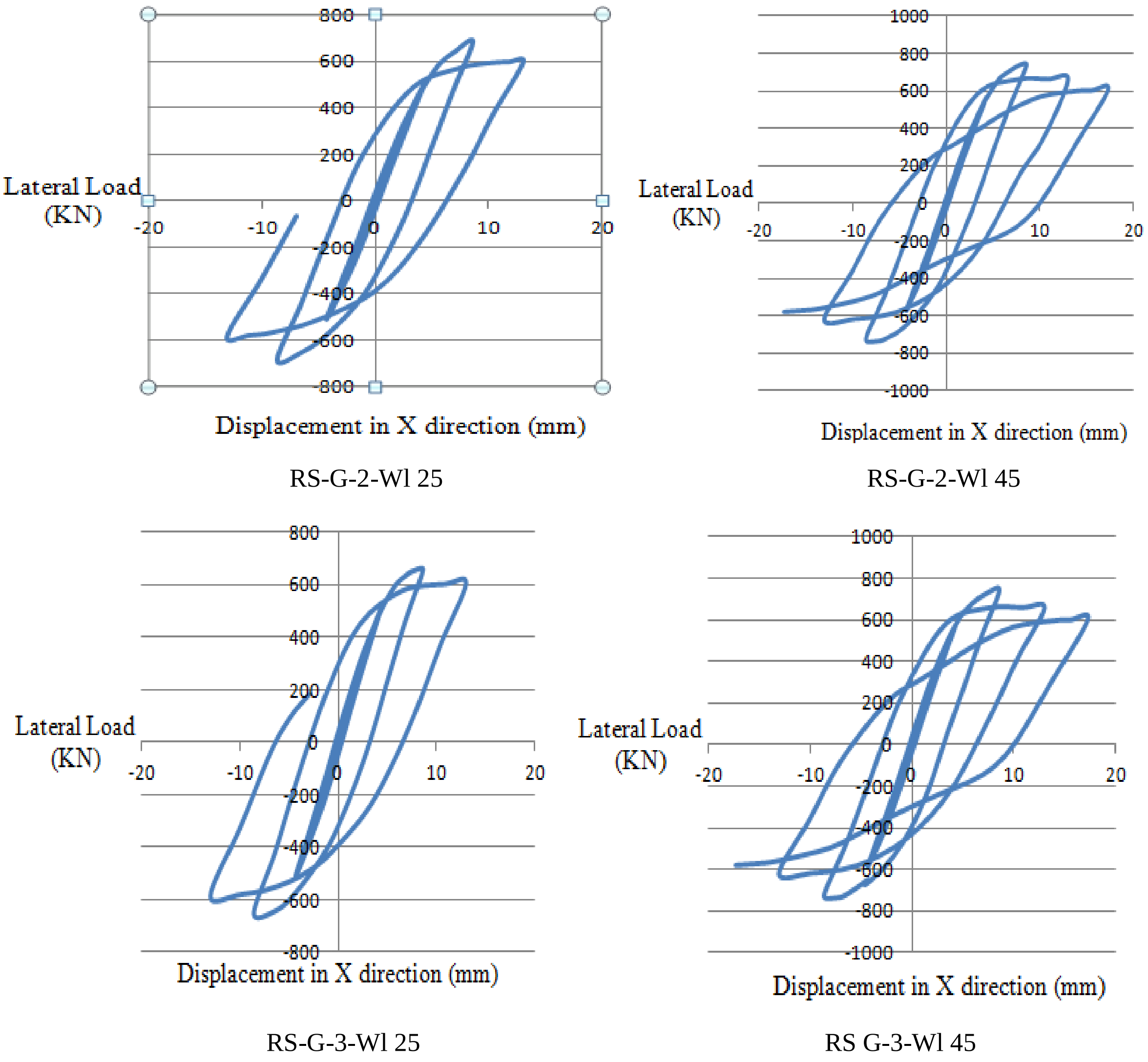


Fig 10: Comparison of hysteresis loop of different width of connecting link

Table 7: analysis results of different width of the connecting link

Model	Strength (kN)	Yielding displacement (mm)	Peak strength (kN)	Stiffness (kN/mm)
RS-G-2-Wl 25	602.5	6.1	687	79.709
RS-G-2-Wl 45	642.14	5.375	734.38	80.335
RS-G-3-Wl 25	602.81	6.91	656.45	88.76
RS-G-3-Wl 45	643.91	6.048	741.68	89.2

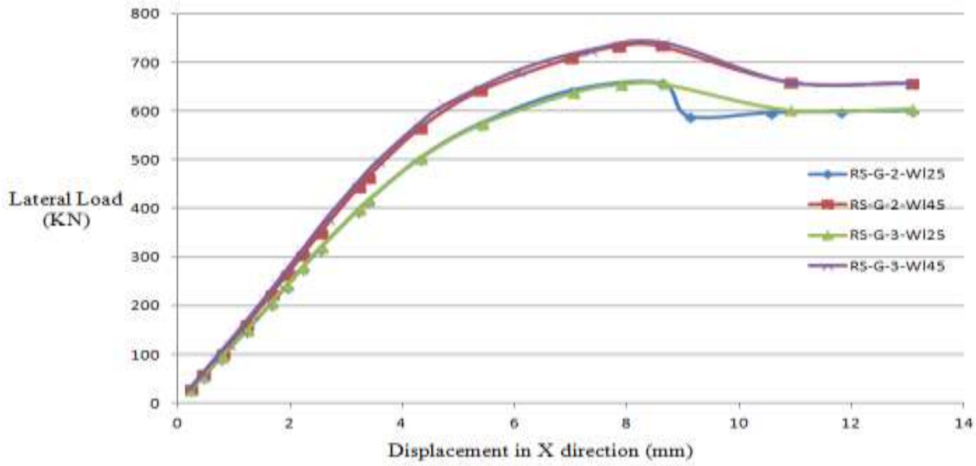


Figure 11: Comparison of monotonic load - displacement graph of different width of connecting link

Another important parameter is the width of the link. While comparing models of RS-G-2-Wl 25 and RS-G-2-Wl 45, it is clear that RS-G-2-Wl 45 has maximum energy dissipation than that of RS-G-2-Wl 25. Same pattern of energy dissipation is found in the models of RS-G-3Wl 45 and RS-G-3-Wl 25.

While comparing all four models it is found that, RS-G-3-Wl 25 and RS-G-3-Wl 45 have strength and stiffness more than that of RS-G-2-Wl 25 and RS-G-2-Wl 45. The strength of RS-G-3-Wl 25 is increased by 22.1 kN than that of RS-G-2-Wl 25. Similarly the strength of RS-G-3-Wl 45 has increased by 16.87KN than that of RS-G-2-Wl 45. Similar trend was observed in the case of stiffness also.

Comparing the models of RS-G-2-Wl 25 and RS-G-2-Wl 45, it is observed that, RS-G-2-Wl 45 has stiffness 47.38kN more than that of RS-G-2-Wl 25. Similar trend was observed in the models of RS-G-3-Wl 25 and RS-G-3-Wl 45. While comparing RS-G-2 and RS-G-3 with different width of the link, it is found that RS-G-3has more peak strength as well as yielding displacement than that of RS-G-2.

It was found that width of the link would govern the hysteretic behavior of the shear wall. Use of very thin link (Specimen RS-G-2-Wl 25& RS-G-3-Wl 25) may results in small stiffness and negligible energy dissipation. After the non linear analysis of all four models it is found that, wide rings increase the strength of the shear wall.

3. CONCLUSION

RS-SPSW is an effective technology that can be used to increase lateral resistance of a building. Shear buckling of ordinary SPSW occurred at a load that is approximately half the shear capacity. But RS-SPSW limits the out of plane buckling by mechanics of how the circular ring deformed in to an ellipse. Finite element analysis is conducted over 16 shear panels to study the effect of geometrical parameters on RS-SPSW under cyclic loading. Cyclic load was provided on the basis of ACT 24 protocol. A non linear static analysis was conducted by using ANSYS 14.5 software.

Different geometrical arrangements of RS-SPSW are analyzed. The steel plate shear wall with rings arranged along perimeter (RS-G-3) as well as aligned ring models (RS-G-2) shows nearly full hysteretic behavior. In addition to this they are capable of developing plastic hinges. After the analysis of RS-G-2 and RS-G-3 it is clear that, thicker plate exhibits full hysteretic behavior and does not experience substantial strength and stiffness reduction. On the other hand thinner plate experience buckling at earlier stage and shows smaller energy dissipation ratio. The behavior of RS-SPSW is highly sensitive to the size of the ring units. For RS-G-2 and RS-G-3 with smaller ring radius gives higher strength characteristics, but rings with larger radius shows more ductility. Another input parameter that had a major influence on the hysteretic behavior of RS-SPSW is width of the connecting link (Wl). Based on the finite element analysis, it is observed that for wider Wl shows tremendous increase in strength, stiffness and energy dissipation. From the analysis of all parameters it was absolutely clear that RS-G-3 behave stronger and stiffer than RS-G-2, conversely energy dissipation and ductility property is more for RS-G-2 than that of RS-G-3. So it can be concluded that on the basis of strength characteristics, RS-G-3 is better than RS-G-2.

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