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Behavior of Steel Plate Shear Wall with Constrained Ring Holes

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Abstract- Steel Plate Shear Walls (SPSWs) are used for lateral load resisting systems for both new and retrofit construction. Generally, thin plate shear walls used, but it shows buckling at small loads which results in highly pinched hysteretic behaviour. In order to reduce buckling, constrained ring holes are provided in steel plate. It also uses simple shear beam-column connections. Ring like cut-outs elongate into an ellipse when the shear plate is loaded laterally. The transverse and longitudinal deformations of a circular ring that is stretched into an ellipse are nearly equal. When the rings are provided in the direction perpendicular to the tension diagonal, the slack in the compression diagonal direction will be removed. This reduces buckling. It is more economic, since it requires less steel and no moment connections between beams and columns. It will reduce the pinching in hysteresis loop and provides comparatively good strength and stiffness compared to thin unstiffenedsteel plate shear wall. The present study deals with the buckling and seismic behaviour of steel plate shear wall with ring cut-outs by considering various input parameters like configuration of cut-outs and thickness of web plate.

Index Terms -Steel Plate Shear Wall, Constrained ring holes, Simple shear beam column connections, Buckling resistant.

1. INTRODUCTION

Steel plate shear walls (SPSW) is commonly used in construction industry since past many years.The main role and purpose of a steel shear wall is to resist the lateral forces of earthquakes or winds in a building. SPSWs generally use thin plates that are allowed to buckle. Previous studies have shown that SPSWs exhibit good post-buckling capacity and energy dissipation takes place as the web plate yields in the inclined tension field direction. SPSW are ideal for both high rise buildings and mid-rise construction andare commonly used in USA, Japan and Canada.

The principle used in current SPSW design is that the post-buckling tension field capacity of the thin web plate is proportional to resist the full lateral load. The resulting web plate is thin, buckles at low loads, possesses low stiffness, and does not provide resistance when the lateral loadsare reversed. To compensate for these shortcomings, moment connections are required at the beam to column connections to improve energy dissipation, increase stiffness, and provide lateral resistance during load reversal. The resulting SPSW designs with very thin web plates, moment connections will lead tosignificantly larger beams and columns than comparable braced frames. This can result in inefficient structural systems.

SPSWs consists of steel plate, columns and beams which are referred to as web plate,vertical boundary elements (VBE) and horizontal boundary elements (HBE) respectively. SPSW's are generally placed in one or more bays over the building's height.The beam to column connections may be either simple connections or moment resisting connections.

Steel plate shear walls are preferred over other shear wall systems because it is less costly, gives better performance, and ease of design. There is significant reduction in the self-weight of the system and foundations due to the reduced thickness of the web plate in SPSW. The plan area devoted to SPSW is smaller than Concrete Shear Walls (CSWs). Most importantly, erection of steel plate shear walls takes much lesser time than concrete shear walls. However, SPSW also suffers from buckling at small loads which results in highly pinched hysteretic behavior, low stiffness, and limited energy dissipation. These shortcomings are avoided by a new type of SPSW which contains a unique pattern of cut-outs to reduce buckling. It uses simple shear beam-column connections. This basic ring unit deforms into an ellipse, when lateral forces are applied on the wall. The transverse and longitudinal deformations of a circular ring that is being stretched into an ellipse are nearly equal. When these ring cut-outs provided in the direction perpendicular to tension field, the slack in the compression diagonal will be removed. Thus we can reduce the buckling.

In other words the elongation of the ring in one radial direction will be compensated by the shortening of the ring in the perpendicular radial direction, thus reducing out-of-plane deformation.

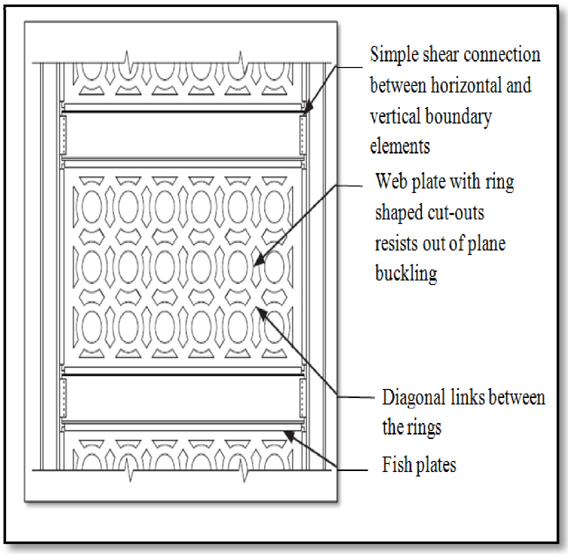


Fig. 1. Ring-shaped steel plate shear wall (Egorova et al., 2014)

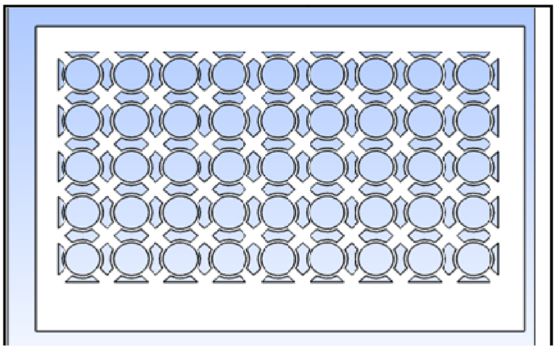
In 1961 K.Basler studied the shear strength of plate girders. By decreasing the web slenderness, he concluded that the web thickness increases and more shear force will be carried in beam action. In 1983, Timler and Kulak tested a large-scale single story steel shear wall test specimen to verify the analytical work done by Thorburn et al. (1983). They applied monotonic loading on the specimen to the serviceability drift limit until the faiulure of the structural system.Gravity loads were not applied. It was observed that there was good agreement and match between predicted and actual principle stresses in the plate and axial stresses in the frame members. Cassese et al. (1993) investigated the seismic behavior of unstiffened thin steel- plate shear walls. The main purpose of the research was to assess and analyze the feasibility of thin plate shear walls and to develop new design methods that can result in more optimal designs. In 1998, Elgaaly performed a series of tests on thin steel plate shear walls under cyclic loading. An analytical model was presentedto determine the behavior of the shear walls. This model could predict the behavior of plates with both bolted and welded connection. Lubell et al (2000) studied the behavior of single and multi-story unstiffened steel shear walls subjected to cyclic quasi-static loading. He concluded that the multi-story specimen was more flexible than the single-story specimen because the influence of the overturning moment is of more significance as the height of the structure increases.Hitaka .T. et al (2003) developed a new type of earthquake-resisting element, which consisted of a steel plate shear wall with vertical slits. In this model, the steel plate segments between the slits acted as a series of flexural links, which provided a good ductile response without any need for heavy stiffening of the wall. Berman, J. W. (2005) compared the results from cyclic testing of six frames: four concentrically braced frames (two with cold-formed steel studs for in-plane and out-of-plane restraint of the braces and two without), and two light-gauge steel plate shear walls (one with a flat infill plate and one with a corrugated infill). The largest initial stiffness was observed in a braced frame specimen with cold formed steel studs and the largest ductility was achieved with a steel plate shear wall with flat infill.Chan R. et al (2011) provided perforations in thicker panels. Nonlinear finite element technique was used to check the effect on stiffness and strength. Based on the results, a simple linear reduction function was proposed.GhassemiehM. et al (2014) studied the dynamic and cyclic behavior of steel plated shear wall. Finite element method of analysis was implemented in order to simulate the behavior of such a wall structure. The strength and ductility of the system obtained from the analysis were compared with those of steel shear wall tests reported before. The parameters of the steel shear wall system such as plate thickness, column and beam stiffness and the plate aspect ratio were recognized and their effects were recorded. The effect of stiffeners on the behavior of the SPSWwas also investigated.Bhowmick A. K. (2014) examined the behavior ofunstiffened thin steel plate shear walls with circular perforations placedat the center of the infill plates.A shear strength equation was developed for perforated steel plate shear wall with circular perforation at the center. Ugale, A. B. et al (2014) described the analysis and design of high-rise steel building frame with and without Steel plate shear wall (SPSW). The analysis of steel plate shear wall and the building are carried out using Software STAAD PRO. The main parameters considered were used to compare the seismic performance of buildings such as bending moment, shear force, deflection and axial force also focused on the effects comes on the steel structure with and without shear wall. Egorova .N. et al (2014) developed a new type of steel plate shear wall (SPSW) which resists out-of-plane buckling by providing ring cut outs on web plate.The ring shaped portions of steel is connected by diagonal links. This buckling resistant SPSW exhibited full hysteresis behavior and improved stiffness than thin unstiffened SPSW.

The main aim of this report is to develop a more efficient and high performance shear wall system. The study of buckling and seismic behavior of steel plate shear wall with ring cut-outs by considering various input parameters like configuration of cut-outs, and aspect ratio of plate those were not considered in the previous studies.

2. FINITE ELEMENT MODELING AND ANALYSIS

Modeling was done using CATIA v5 and analysis was done using finite element software ANSYS 12. For the material properties, stress- strain behavior of6.3 mm thick A 36 steel was used. The Young’s modulus was taken as 2.1×10^5 N/mm^2 and Poisson’s ratio for the steel was taken as 0.3 respectively. SHELL 181 was used for the analysis of steel plate.

The boundary elements were assumed to be perfectly rigid. Panel considered was single storied. The first set of specimens consisted of 824x824 mm steel plate with the S75x8 Canadian section for the beams and columns. The next 2 setswere of column with flange width 300 mm and total height 500 mm and thickness of flange 28 mm and that of web 14.5 mm respectively. Beam with flange width 300 mm and total height 400 mm and thickness of flange 24 mm and that of web 13.5 mm respectively. All nodal degrees of freedom were constrained at the base of the shear wall. The out of plane degrees of freedom of column and beam nodes were restrained. The connection between beams and columns were provided using constraint equation (the coupling option in ANSYS) fixing all degrees of freedom except in plane rotation. The beam and the edge of the panel was connected using constraint equation fixing the translational degrees of freedom. Lateral displacement was applied to the outer flange of the top beam. Loading which was applied was displacement controlled. The loading protocol was adopted from AISC seismic provisions (Appendix S6.2) but was modified such that only one cycle per story drift level was used. These displacements were cyclic in nature and went up to 3% drift where drift ratio is defined as the displacement of the load point divided by the distance between the load point and the center line of shear wall. Large displacement analysis was executed in order to find the out of plane displacement across the width of plate. Various arrangements of ring cut outs are shown in Fig 2 and 3.



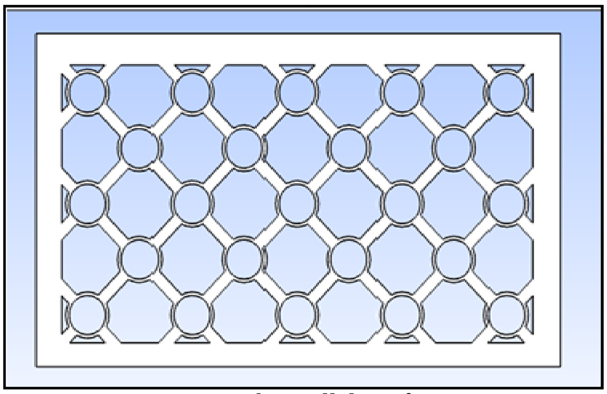


Fig. 2. Cut outs with parallel configuration

Fig. 3. Cut-outs with staggered configuration

Table 1. Details of specimens

Set No:	Spec. Name	Specification
1	A1	Specimen without cut-outs
1	A2	Specimen with cut-outs (parallel)
2	B1	Specimen with cut-outs (parallel)
2	B2	Specimen with cut-outs (staggered)
3	C1	Specimen with cut-outs (parallel) – thickness - 6mm
3	C2	Specimen with cut-outs (parallel) – thickness - 9mm
3	C3	Specimen with cut-outs (parallel)- thickness -12mm
4	D1	Specimen with cut-outs (staggered)- thickness 6mm
4	D2	Specimen with cut-outs (staggered)-thickness 9mm
4	D3	Specimen with cut-outs (staggered)-thickness 12mm

Next set was used to find the effect of configuration of cut-outs in the structure. Parallel and staggered types were used to arrange the cut-outs on steel plate.

Table 2. Geometric details of specimens

Spec. Name	l (mm)	b (mm)	R_o (mm)	W_l (mm)	t (mm)
A1	824	824	-	-	2
A2	824	824	48	18	6
B1	3657	6096	216	119	6
B2	3657	6096	216	119	6
C1	3657	6096	216	119	6
C2	3657	6096	216	119	9
C3	3657	6096	216	119	12
D1	3657	6096	216	119	6
D2	3657	6096	216	119	9
D3	3657	6096	216	119	12

Last two sets were used to find influence of thickness of the plate on the structural system with different configurations of ring cut-outs. Various thicknesses of 6 mm, 9 mm and 12 mmare considered.

3. OUT PUT PARAMETERS

3.1 *Strength and stiffness*

Strength, stiffness of a shear wall system was found by applying Monotonic loading. The load displacement graph was generated. Stiffness was noted using the initial slope of curve taking the origin (0, 0) and the point on the curve which corresponds to the half of the maximum strength achieved.

3.2 *Buckling ratio*

This parameter denotes the relative percentage of global tension buckling and lateral torsional buckling of the rings. Shear wall's energy dissipation capacity will be affected by this type of buckling. The out-of-plane displacement across the width of web plate was recorded to find the buckling ratio. This data was then converted in to discrete Fourier transformfunction using MATLAB to separate the differentwavelengths of the input signal (here the variation of out-of-plane displacement). The buckling ratio was calculated by taking ratio of magnitude of most prominent peak and the peak with the next highest magnitude.

4.1 RESULTS & DISCUSSION

4.1 *Effect of ring cut-outs on the SPSW*

Load displacement graph of specimen A1 and A2 are shown in fig. 4-5. Specimen A1 shows highly pinched hysteresis behavior under small loads. But the specimen A2 shows fully hysteresis behavior and very small amount of buckling due to cyclic loading. Therefore specimen A2 shows high energy dissipation capacity than A1. There is no large difference in stiffness value of both specimens. The contour plot of out of plane displacement of specimen A1 is shown in fig 13. Its graphical representation across width of plate is shown in fig. 12

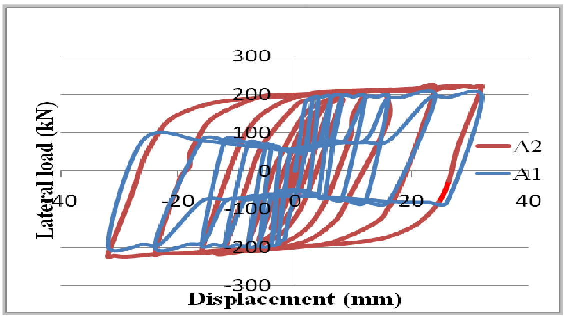


Fig . 4. Load- displacement graph of specimen A1& A2

4.2. *Effect of configuration of ring cut-outs on SPSW*

The load deformation curve of specimens B1 and B2 are shown in Fig. 6 – 7. It shows that staggered arrangement results in lower strength as compared to parallel type configuration. However, the staggered arrangement also shows a fully hysteresis with almost no pinching.

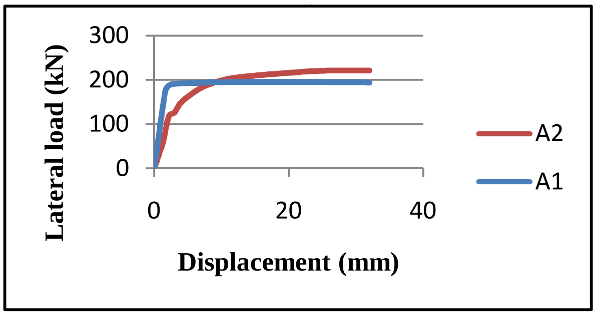


Fig. 5. Load- displacement graph of A1& A2

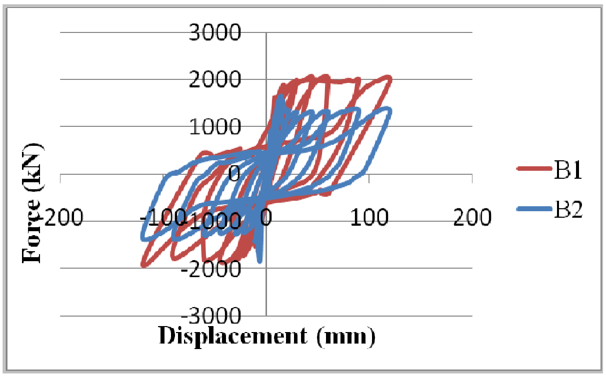


Fig. 6. Load- displacement graph of B1 & B2

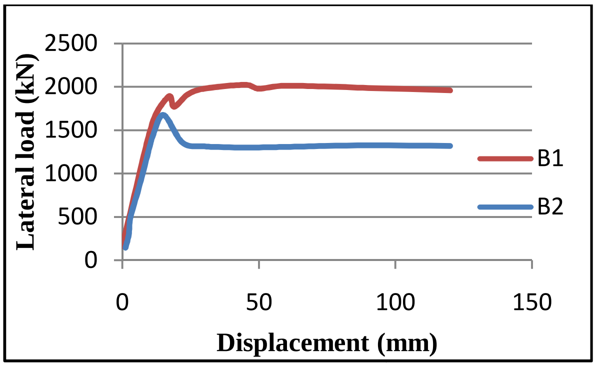


Fig. 7. Load- displacement graph of B1 & B2

4.3 Effect of platethickness with parallel configuration

The load deformation curve of specimens C1,C2 and C3 are shown in Fig. 8- 9.It can be seen that the shear strength and the stiffness increases as the thickness of plate increases. But buckling ratio reduces as the plate thickness increases.

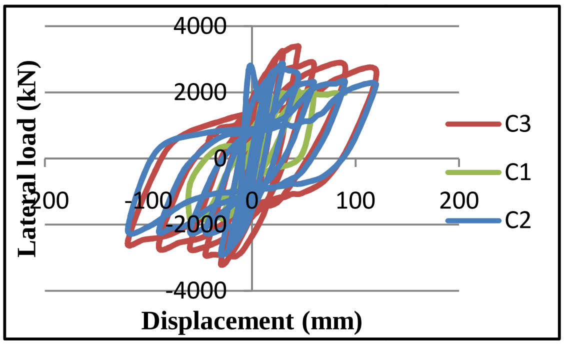


Fig. 8. Load- displacement graph of C1,C2& C3

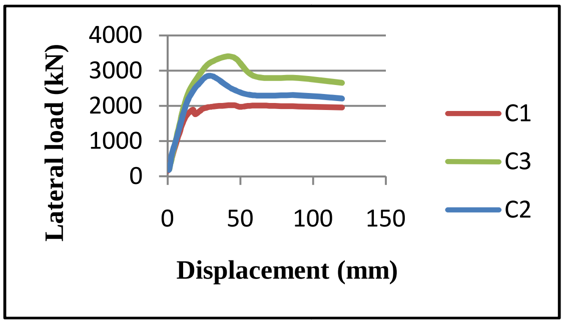


Fig. 9. Load- displacement graph of C1,C2& C3

4.4 Effect of platethickness with staggered configuration

The load deformation curve of specimens D1, D2 and D3 are shown in Fig. 10- 11. As in the case of parallel type configuration, here also shear strength and the stiffness increases as the thickness of plate increases. Buckling is reduces as the thickness increases. Out- put parameters and results are shown in Table 3.

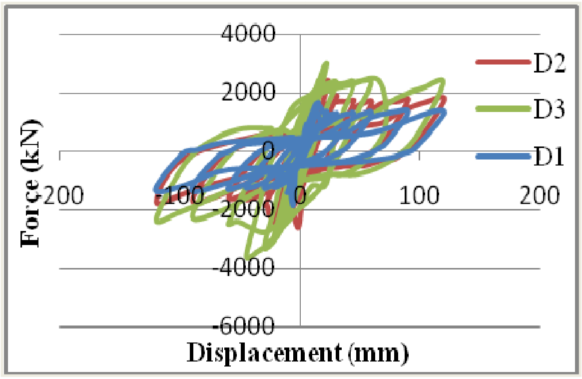


Fig. 10 Load- displacement graph of D1, D2 & D3

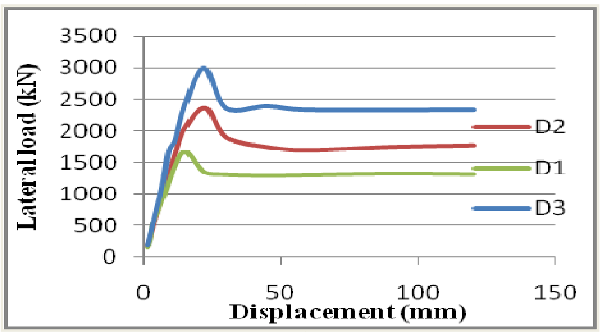


Fig. 11. Load- displacement graph of D1, D2 & D3

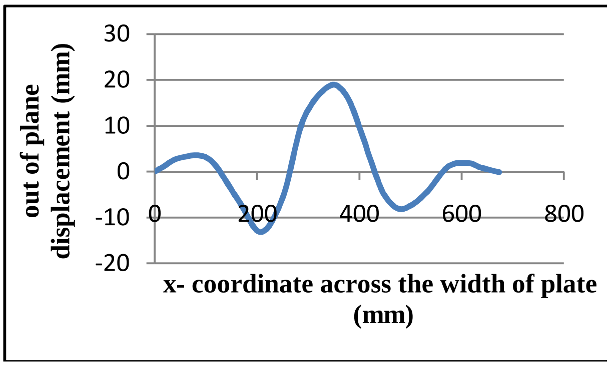


Fig. 12.Out of plane displacement of specimen A1 across width of plate

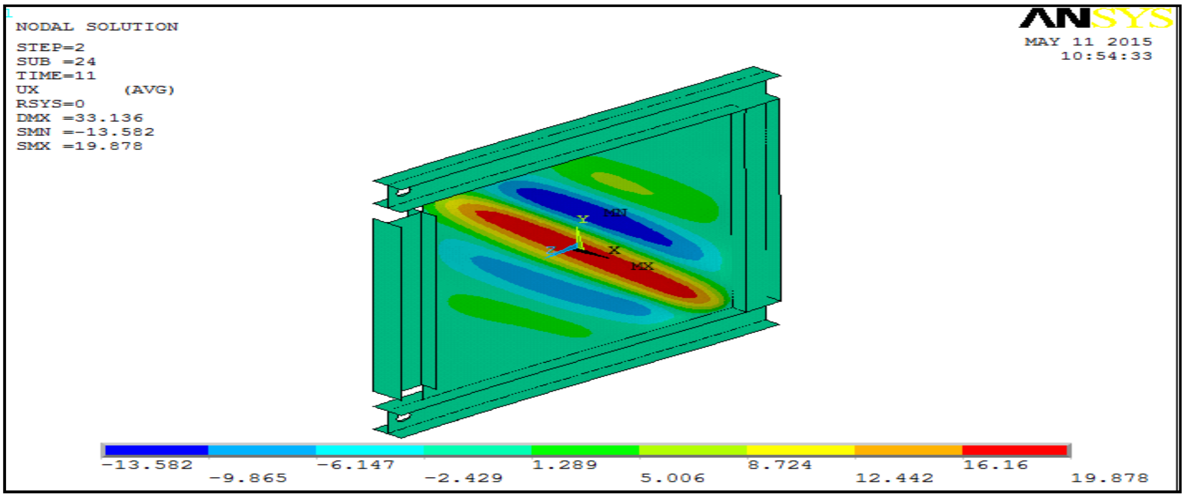


Fig. 13.Out of plane displacement of specimen A1

Table 3. Output parameters & results

Spec. Name	Peakstrength (kN)	Stiffness(kN/mm)	Buckling ratio
A1	193	97	28
A2	221	73	2
B1	2022	174	5
B2	1675	128	16
C1	2022	174	5
C2	2278	183	4.6
C3	3388	211	4
D1	1675	128	16
D2	2357	142	12.5
D3	2995	176	7

5. CONCLUSIONS

- Conventional type steel plate shear wall shows buckling at small loads and reduces its energy dissipation capacity.
- The SPSW with ring cut outs will reduce buckling and shows fully hysteresis behavior
- The cut outs with arrangements parallel and staggered type shows comparatively full hysteresis loop
- In the case of staggered type, the rings are arranged in 45^0, will increase the distance between the rings. The lesser number of rings in the panel, results in lower strength. Also, this leads to decrease in the initial stiffness of the staggered panel.
- Thickness of web plate shows a vital role in all behavioral aspects of shear wall. A thicker plate exhibits a fully hysteresis behavior and greater strength and stiffness. This results in relatively larger energy dissipation.

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