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Structural Performance of Different Forms of Corrugated Plate Shear Walls under Dynamic Loading

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Abstract Steel plate shear wall systems are currently utilized in resisting seismic loading in multistory buildings within seismic prone regions. They consist of infill plates that are bounded by a surrounding frame. Nonlinear push over and cyclic analyses were carried out to study different forms and configurations of horizontal trapezoidal corrugated steel plate shear walls, namely singly corrugated, doubly corrugated as well as perforated corrugated steel plate shear walls. A finite element model was developed for a horizontal trapezoidal corrugated steel single plate shear wall (OPSW) using Abaqus software. It was validated. Thereafter, while maintaining the original overall properties, a parametric study was carried out to investigate the effect of changing plate thickness, plate width/height ratio, deeper corrugations, providing double plates, as well as perforations on the seismic behavior of steel plate shear walls. The paper aims at achieving a better understanding of the main parameters that control the optimum performance of the horizontal trapezoidal corrugated steel shear walls. Few studies have discussed this matter, so the current study comes to fill the gap. It is concluded that double horizontal trapezoidal corrugated plate shear walls (DPSW) are very efficient shear wall systems. They experience stable hysteretic cyclic loops. They have higher shear stiffness, higher buckling load, and higher ultimate strength as well as higher residual strength than OPSW. They also experience higher ductility and more energy dissipation compared to OPSW. Perforations were found to reduce the contribution of the corrugated plate shear wall in resisting the seismic forces, as well as the subsequent reduction of the wall strength and stiffness.

Keywords Dynamic Analysis of Shear Walls, Steel Plate Shear Walls, Corrugated Steel Shear Walls

1. Introduction

Infill steel plate shear walls are efficient in resisting earthquake action within high seismic zones. Previous research asserted their advantages in terms of load carrying capacity, ductility, light weight, as well as energy dissipation capacity beyond the steel strain energy density threshold [1]. These systems are appropriate for new structures as well as in retrofit construction. Intact steel plate shear walls possess relatively low shear rigidity. Thus, the developed base shear is relatively low compared to the developed base shear in reinforced concrete shear walls. Nonetheless the high slenderness ratio experienced in the intact steel plates may lead to immature failure due to buckling instability. Stiffened plates have lower slenderness ratios and consequently higher buckling strengths. However, their construction cost is high. A less expensive solution is the horizontal trapezoidal corrugated steel plate shear walls (OPSW). OPSW's have higher in plane as well as out of plane stiffness and strength. They experience high ductility and stable hysteretic traits as well as tangible energy dissipation capacity, compared to intact steel plates [2-4]. Zhao et al. [5] conducted a comparative study for corrugated steel plate and intact steel plate shear walls, and they concluded that in the case of corrugated steel plate shear wall with shallow corrugations, 25% reduction in load carrying capacity was obtained compared to that of the intact plate, while with deep corrugations the load carrying capacity of steel corrugated shear wall increased by 5% compared to that of the intact plate. However, the energy dissipation capacity and the initial stiffness increased by 26% and 34% in shallow and deep corrugated plates respectively.

Bahrebar et al. [6] presented a performance study on a trapezoidal corrugated perforated plate; they concluded that the load carrying strength of the corrugated plates is substantially decreased on providing perforations.

In order to improve the shear rigidity of corrugated shear walls, Tong et al. [7] presented the double corrugated shear walls that have an enhanced shear resistance capacity that prevails in the closed sections compared to the open section existing in the single corrugated plate shear wall. They also concluded that both the ultimate strength capacity and the post ultimate strength capacity, namely the residual strength are improved in the case of corrugated double sheets.

This paper involves nonlinear pushover and cyclic analyses using Abaqus. The importance of this paper is that it delivers a comparative and comprehensive study on the seismic behavior of the different forms of horizontal trapezoidal corrugated steel plate shear walls, namely singly horizontal trapezoidal corrugated plates shear walls, doubly horizontal trapezoidal corrugated steel plates as well as perforated horizontal trapezoidal corrugated plates shear walls. Few studies have discussed this matter, so the current study comes to fill the gap.

2. Problem Statement

This study investigates a structural solution that is cost effective. Nonetheless it is an enhanced alternative, as it possesses the relatively high initial stiffness and larger buckling strength owing to its enhanced out of plane stiffness. The corrugated plates exhibit accordion behavior, and interactive buckling in lieu of global buckling that takes place in stiffened plate shear walls. The work involves investigating the ultimate strength and the post ultimate strength, namely the residual strength of the double corrugated shear wall, as well as the ductility and energy dissipation that takes place beyond the material strain energy density. The study also investigates whether the corrugated plates are an efficient replacement that is capable of developing the proper internal forces and couple that are able to take and balance the seismic loading while avoiding large base shear. A rather challenging issue in reinforced concrete shears walls of substantial shear rigidity that causes the development of large shear and flexure in the structure, to be transferred from top and all the way down to the foundations. Nonetheless, despite the advantages of the intact steel plate shear wall system over the reinforced concrete shear walls and the eccentrically steel braced frame, its main concerns are the relatively weak shear buckling strength as well as the relatively weak strength capacity. Utilizing double corrugated steel plates would provide the required flexural strength owing to the increase of flexural stiffness as well as shear strength as a result of having a closed section compared to the open section in the case of single corrugated shear wall. The double corrugated steel plates exhibit the desired ductility and energy dissipation, while maintaining a relatively low base shear value owing to the steel plasticity beyond steel Von Mises (σ_{eq}) yield strength and inhibit the lateral buckling experienced in plane stress members under in plane axial load owing to the inevitable imperfections in geometry as well as possible load eccentricity. The double corrugated steel plates when properly designed will have the appropriate buckling strength that permits the utilization of the total capacity of the corrugated steel plate so that material yielding would take place prior to failure.

In seismic retrofit measures, the double corrugated infill shear walls represent an excellent choice for existing structures. They can be replaced if impaired by a strong earthquake action.

Based on the aforementioned, this paper investigates a structural solution that could be an efficient and cost-effective replacement for the reinforced concrete shear walls. It provides the required ductility and energy dissipation.

In order to study the effect of changing some parameters in the steel shear wall on the overall performance, several finite element models were constructed maintaining the original overall properties and dimensions of the validated finite element model.

Modelled specimens are given abbreviations to facilitate the investigation and according to the following:

- Original calibrated horizontal corrugated plate shear wall: OPSW
- Horizontal corrugated plate shear wall with deeper ribs: MPSW
- Double corrugated plate shear wall: DPSW
- Horizontal corrugated plate shear wall with square opening: SOPSW
- Horizontal corrugated plate shear wall with circular opening: COPSW
- Horizontal corrugated plate shear wall with increased plate thickness: TPSW
- Horizontal corrugated plate shear wall with reduced b/h ratio: LPSW

Assumptions

- The plate material is homogeneous. It is isotropic and the steel constitutive model is bilinear elastic perfectly plastic.
- Plane sections originally normal to the neutral plane remain normal to the neutral plane after bending.

3. Validation of the Finite Element Model

In general, two kinds of errors may occur on carrying out finite element analysis. Discretization error, if improperly sized finite elements are adopted, and modeling error on selecting the wrong element type that does not properly simulate the behavior of the investigated structural member in terms of kinematics, equilibrium and behavior. Obtained Finite element analysis results were validated for the case of original calibrated horizontal trapezoidal corrugated plate shear wall (OPSW). A finite element model was constructed using Abaqus CAE software. It is identical in all aspects, namely geometry, mechanical properties, load, and boundary conditions to an experimental test carried out on a horizontal trapezoidal corrugated plate shear wall specimen published by Emami et al. [8]. Dynamic explicit finite element analysis was performed to capture the shear wall behavior from the first yielding to tension field development up till tearing of the infill plate and loss of the shear strength capacity of the system.

Figure 1. Set up of the tested horizontal trapezoidal corrugated specimen (OPSW) [8]

The experimental study simulated an earthquake excitation utilizing a quasi-static cyclic loading test, where the top of one story single bay steel shear wall system was laterally pushed with a hydraulic Jack at prespecified displacement values, while the response of the system was recorded at each loading cycle from the first elastic buckling mode till the tearing of the infill plate and the failure of the shear wall. Only lateral loads were considered. Figure 1 shows the setup of the tested horizontal trapezoid corrugated specimen.

Specimen structural parameters and mechanical properties are given in table 1 and table 2 respectively. Figure 2 shows the corrugated plate profile OPSW. Figure 3 illustrates a superposition of the force displacement hysteresis loops for both the finite element analysis and the experimental testing for OPSW shear wall. It is noticed that base shear forces correspondent to the considered displacement values for both curves are close up to 30 mm drift. Thereafter the finite element analysis resulted in higher base shear compared to the experimental work.

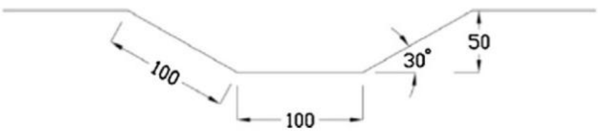


Figure 2. Corrugated plate profile of OPSW

Table 1. Specimen structural details (mm)

Beam	Column	Plate thickness
HE-B140	HE-B160	1.25

Table 2. Mechanical properties

Type	Elastic modulus (GPa)	Fy (MPa)	Fu (MPa)	Fy/fu	% elongation
Plate	210	207	290	0.71	41
Column	210	300	443	0.67	33
Beam	210	288	456	0.63	37

This can be understood and justified by the followings:

- The infill plate is connected to the boundary elements by bolts in experimental work, while in finite element analysis, connecting is via node merging which is more like continuous welding.
- The residual stresses as well as surface imperfections degrade the shear rigidity and the buckling strength of the experimentally tested corrugated plate shear wall.

Thus, the results of finite element analysis are found consistent with the experimental testing findings.

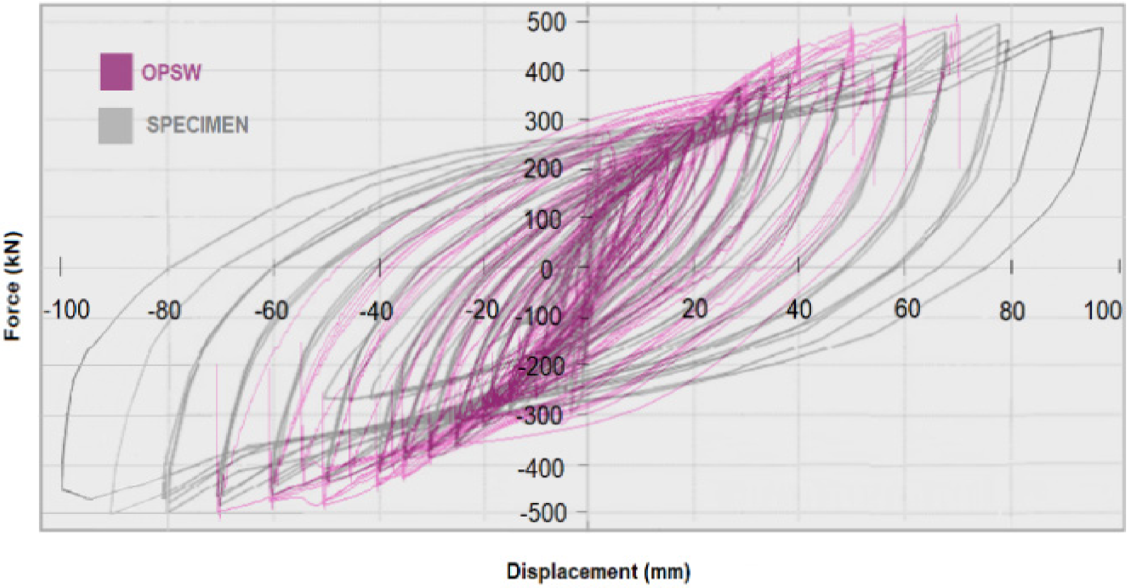


Figure 3. Superposition of Finite element model for OPSW and experimental testing

4. Analysis and Discussion of Results

Design provisions require that the corrugated steel panel should yield before the boundary beams, thereafter the boundary beams yield in accordance with the strong column and weak beam analogy, then the boundary columns. The loading program for the experimentally tested specimen involved gradually increasing of lateral displacement in successive cycles while the displacement amplitude followed an increasing and decaying sequence in accordance with AC154 protocol. Approximate Elastic Displacement (AED) was adopted as 20 mm.

In order to study the effect of changing some parameters in the horizontal trapezoidal steel shear wall on the overall performance, several finite element models were constructed and analyzed, while maintaining the original loading, overall properties, and dimensions of the successfully validated OPSW shear wall model.

4.1. Corrugated Plate of Deeper Corrugations (MPSW)

In the case of MPSW model, the corrugation depth is 70.7 mm, compared to 50 mm rib depth in the OPSW model. The ribs are now condensed by about 19.4 % per meter.

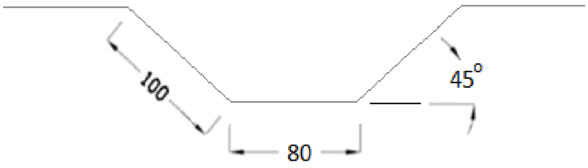


Figure 4. Corrugated plate profile of MPSW

Figure 4 shows the horizontal trapezoidal corrugated plate profile for MPSW shear wall. Figure 5 illustrates the finite element model for MPSW shear wall. Figure 6 illustrates the hysteresis loop for MPSW model. Figure 7 is a superposition of the hysteresis loops pertaining to MPSW and OPSW shear wall models. The superposition indicates that the MPSW model has higher initial stiffness as well as higher ultimate strength compared to the OPSW model.

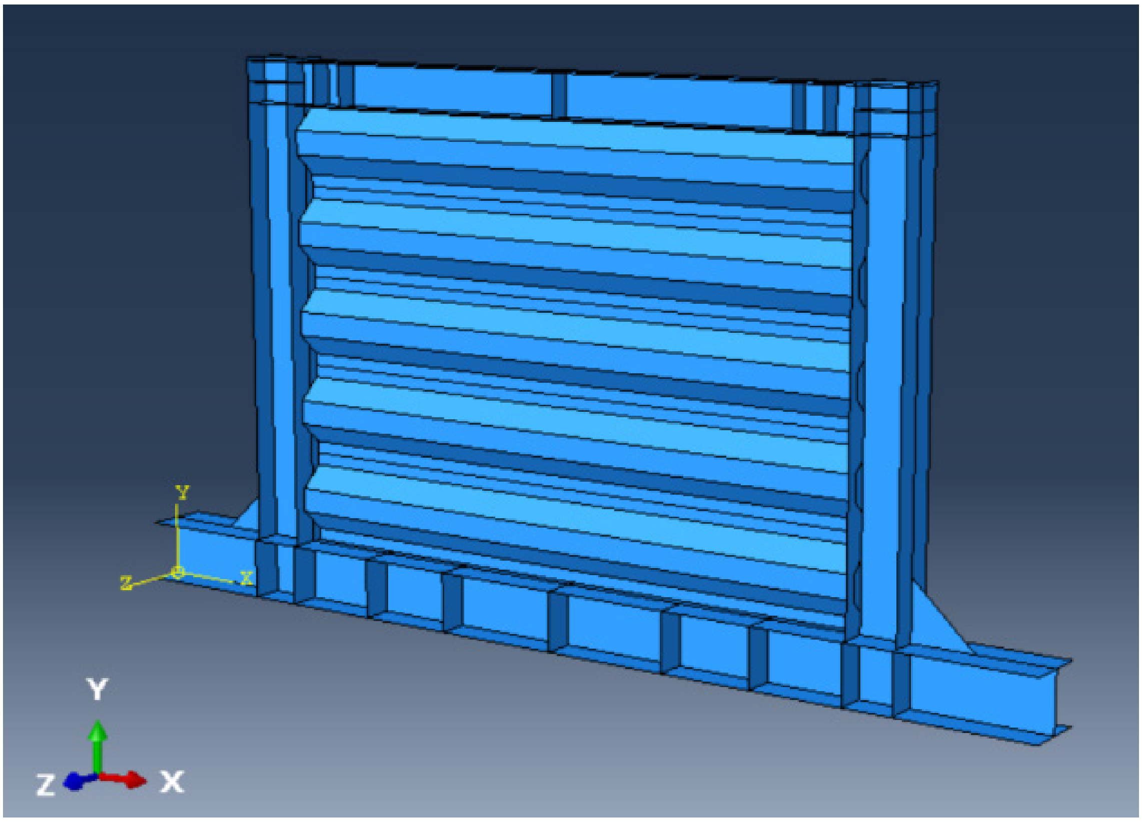


Figure 5. Finite Element of MPSW in Abaqus

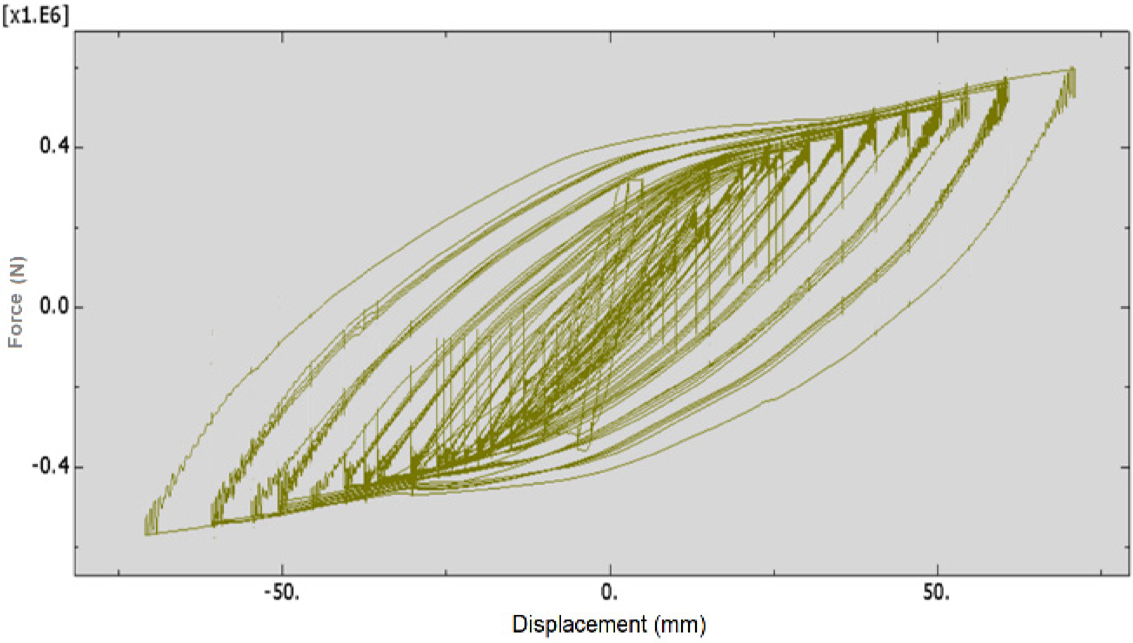


Figure 6. Hysteresis loops for FEM Model of MPSW

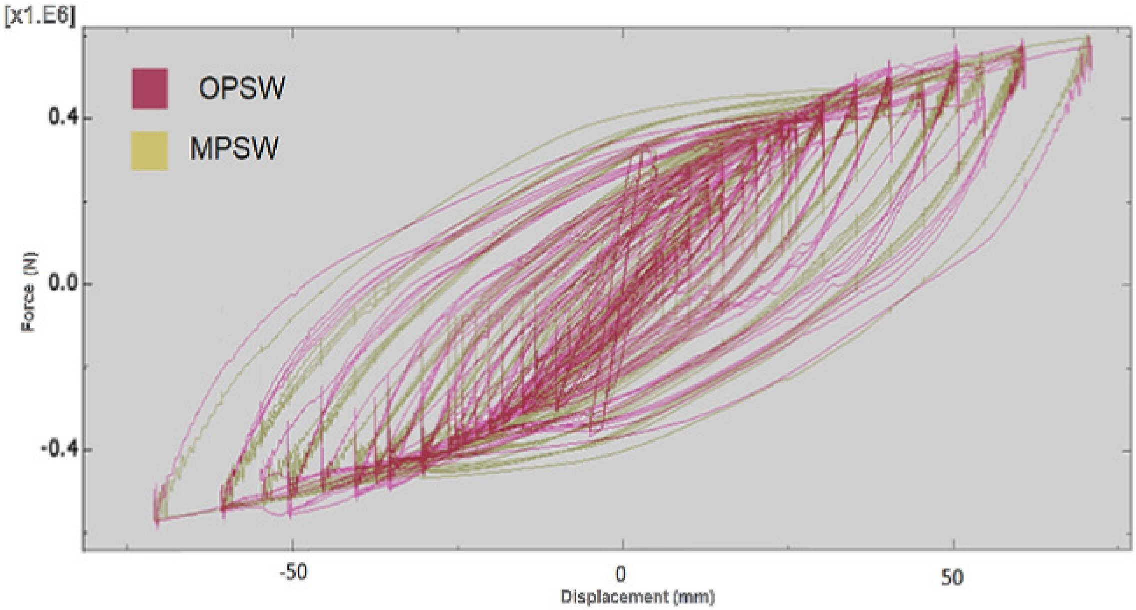
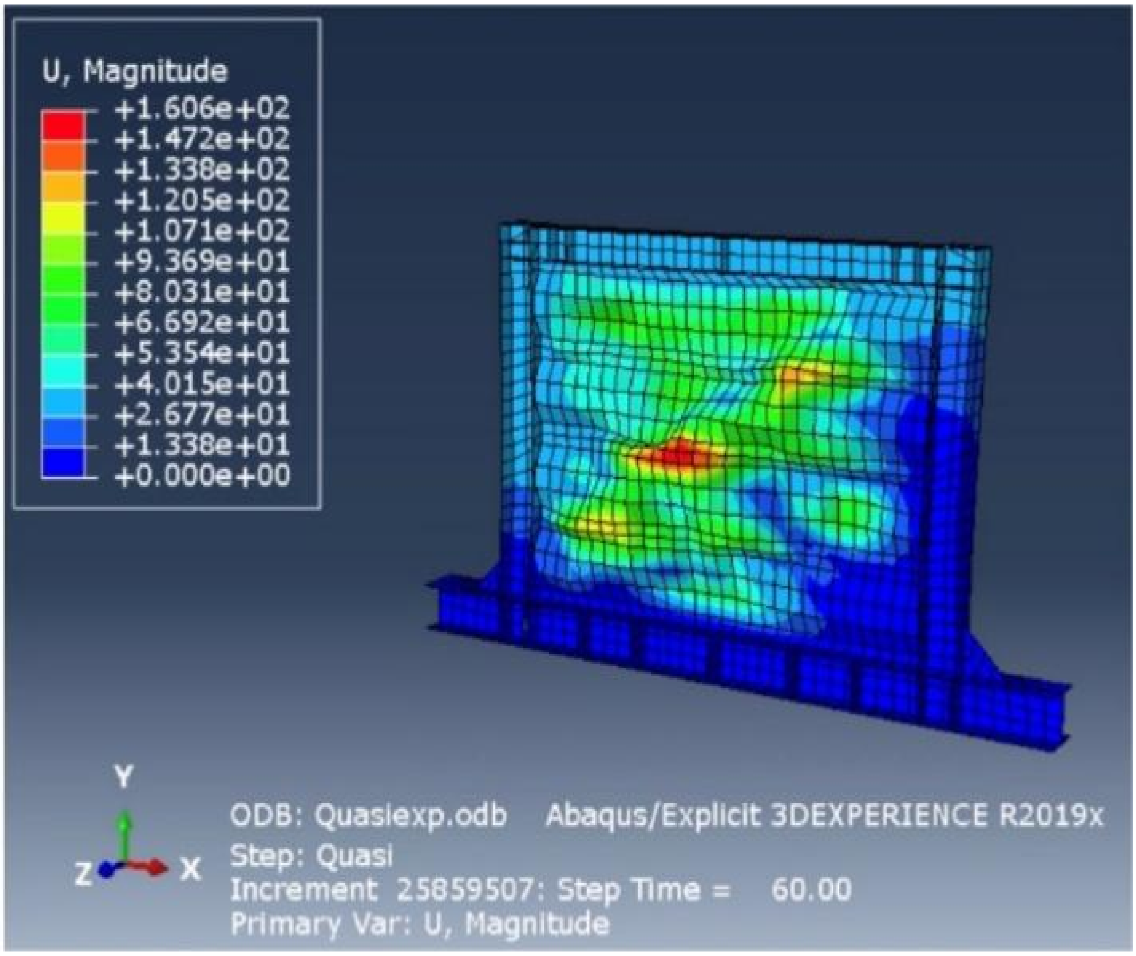


Figure 7. Superposition of the Hysteresis loops for OPSW and MPSW corrugated plates



ODB: Quasiexp.odb Abaqus/Explicit 3DEXPERIENCE R2019x
Step: Quasi
Increment 25859507: Step Time = 60.00
Primary Var: U, Magnitude

Figure 8. Inelastic Deformation of OPSW at Cycle 60

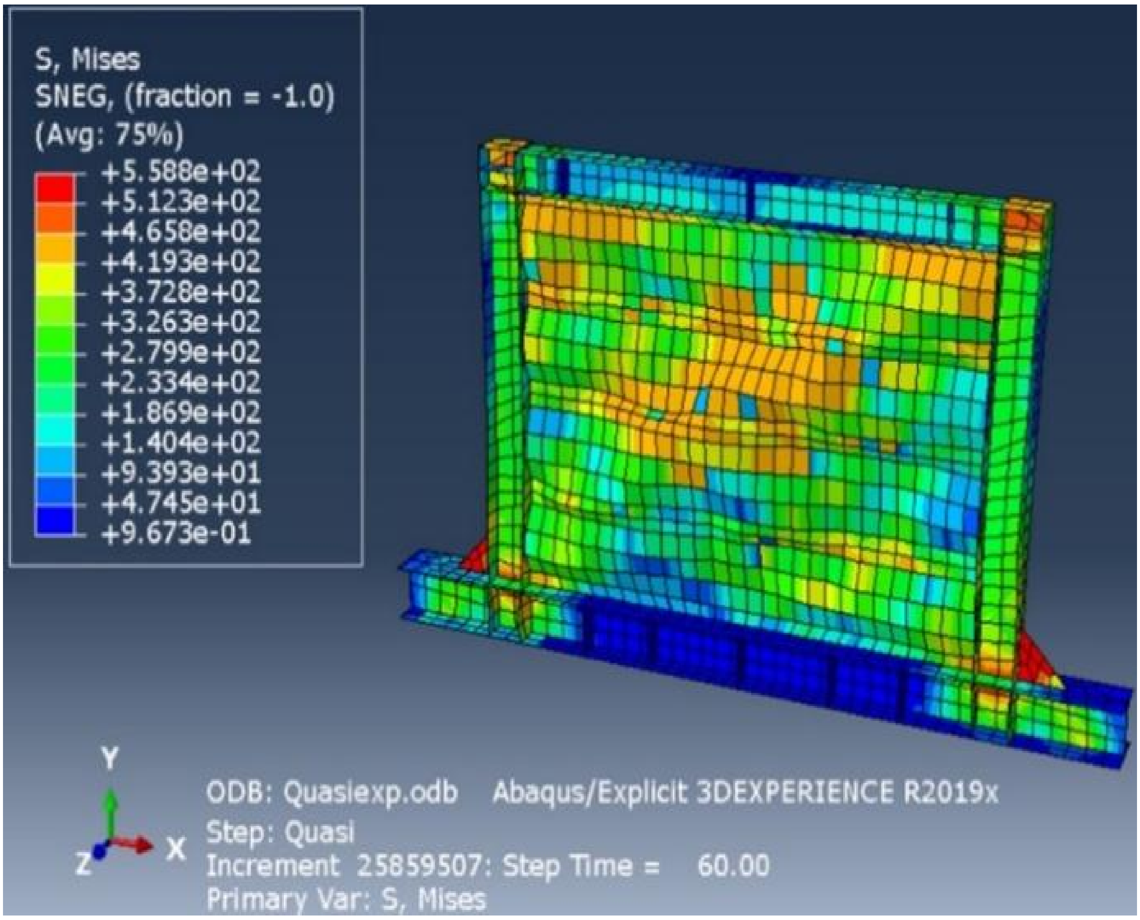


Figure 9. Von mises stresses of OPSW at Cycle 60

It can be noticed that with the deeper corrugations in MPSW model, the shear wall capacity is slightly increased.

Comparing the inelastic deformation output and the Von Mises (σ_{eq}) stress distribution of the infill plate OPSW models in Figures 8, 9 with those pertaining to MPSW models (Figures 10, 11). It can be noticed that the deformation as well as Von Mises (σ_{eq}) stress distribution is experienced in MPSW model across a wider region, compared to OPSW model of shallower corrugation, with a reduction in out of plane deformation in MPSW model of about 20% less than OPSW model.

However, by comparing the superposition of the hysteresis loops for the two FEM models, it can be noticed that the modified section showed a higher stiffness at lower displacement values. This difference starts to diminish at higher displacement cycles as illustrated in Figure 7. The first material yield for the infill plate MPSW occurred at around cycle 3 with drift of nearly 3.0 mm, as opposed to material yield experienced at a drift value of 5.0 mm in OPSW model of shallower corrugations. This indicates improvement of the initial stiffness for the wall with deeper corrugated profiles. The diagonal tension field effect was less. This can be noticed by comparing the inelastic deformation, as well as Von Mises (σ_{eq}) stress distribution at cycle 60 of OPSW in Figures 8, 9 with the case of MPSW model in in Figures 10, 11.

Moreover, Figures 9, 11 pertaining to Von Mises stress (σ_{eq}) distribution for OPSW and MPSW models, indicate that the stress values and the stress distribution are close to those pertaining to OPSW, however the yielded portion of the infill plate in the case of MPSW model distributes along larger regions, indicating that MPSW shear wall has better ductility than OPSW shear wall.

Thus, the performance of the steel shear wall is highly affected by the plate corrugations, namely density of corrugations distribution and corrugation depth. A deeper corrugated plate will have higher initial stiffness as well as higher ultimate strength.

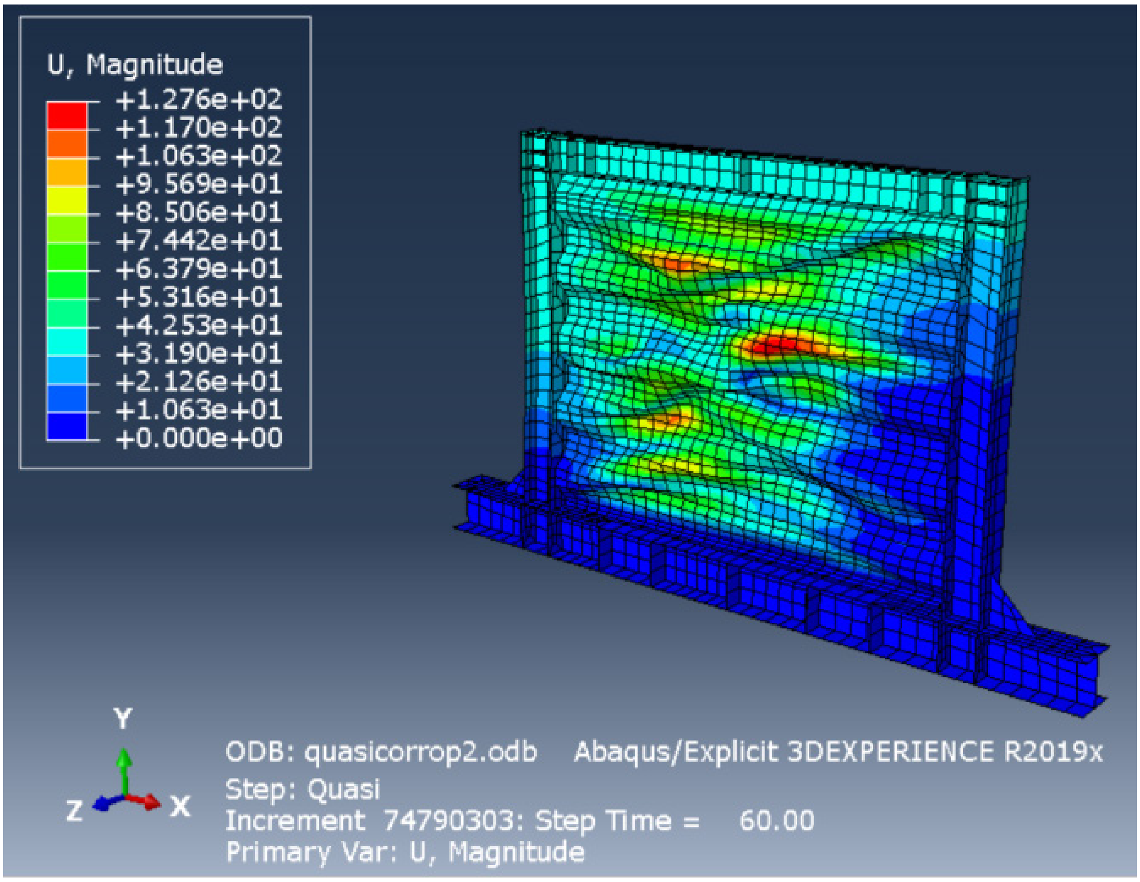


Figure 10. Inelastic Deformation of MPSW at Cycle 60

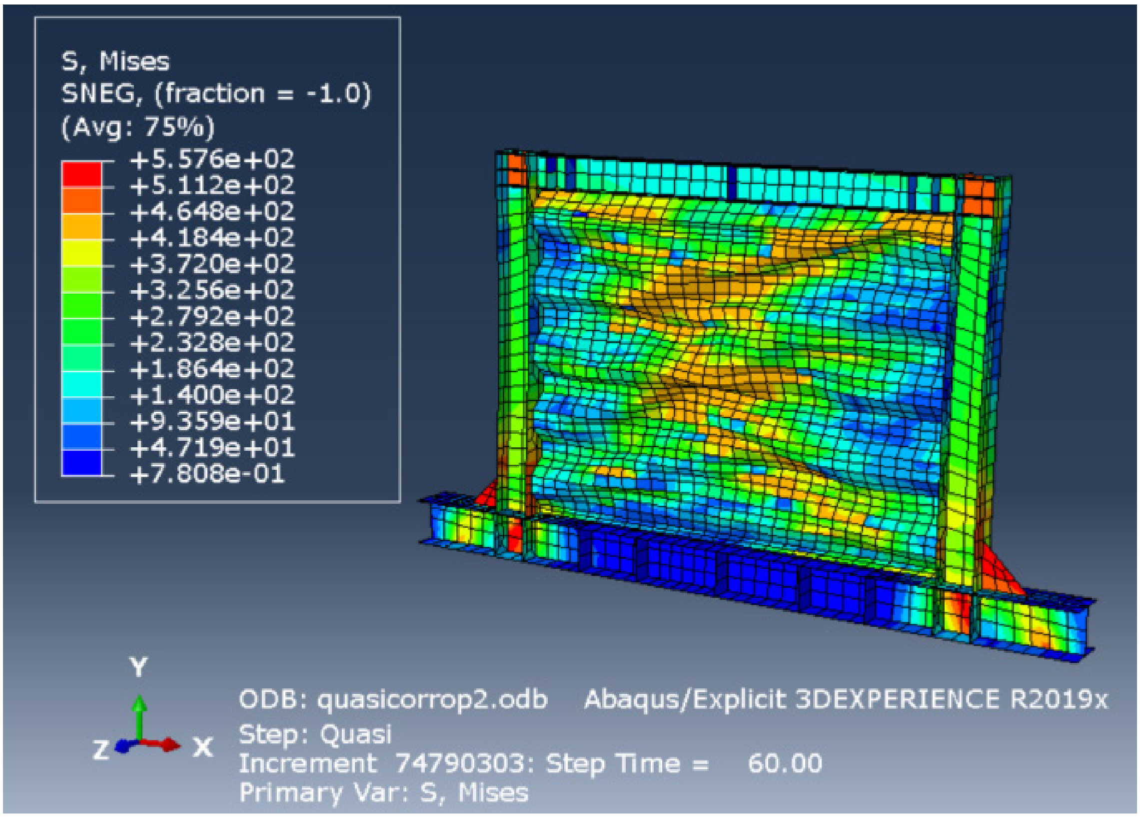


Figure 11. Von mises stresses of MPSW at Cycle 60

4.2. Using Double Horizontal Corrugated Plate (DPSW)

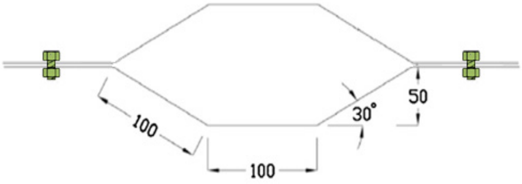


Figure 12. Double Corrugated Sheet profile of DPSW

In this system, two horizontal trapezoidal corrugated plates are joined together through a row of bolts connecting these plates at valley region, as shown in figure 12. The merit of this system is that infill plates are assembled to form closed sections that offer the corrugated steel shear wall a significantly higher initial stiffness that enhances the elastic shear buckling strength. It also provides higher ultimate strength capacity, owing to its larger shear rigidity, as well as higher buckling strength due to its larger slenderness ratio compared to that of OPSW model.

Figure 13 illustrates the hysteresis loops for DPSW model. Figure 14 illustrates a superposition of hysteresis loops for OPSW and DPSW. By comparing both hysteresis loops, it can be noticed that the strength of the shear wall in DPSW model is 38% more than OPSW model.

It is attributed to the fact that the closed sections formed by bolting the two horizontal trapezoidal plates together will have a significantly higher initial stiffness which in its turn will delay the elastic shear buckling and will have a higher range of inelastic deformation. A highly favorable structural response is to against earthquake attack.

Figures 15, 16 indicate that at higher cycles, the DPSW model experiences inelastic deformation and Von Mises Stresses (σ_{eq}) distributed at relatively large region compared to that of a single corrugated plate shear wall OPSW model.

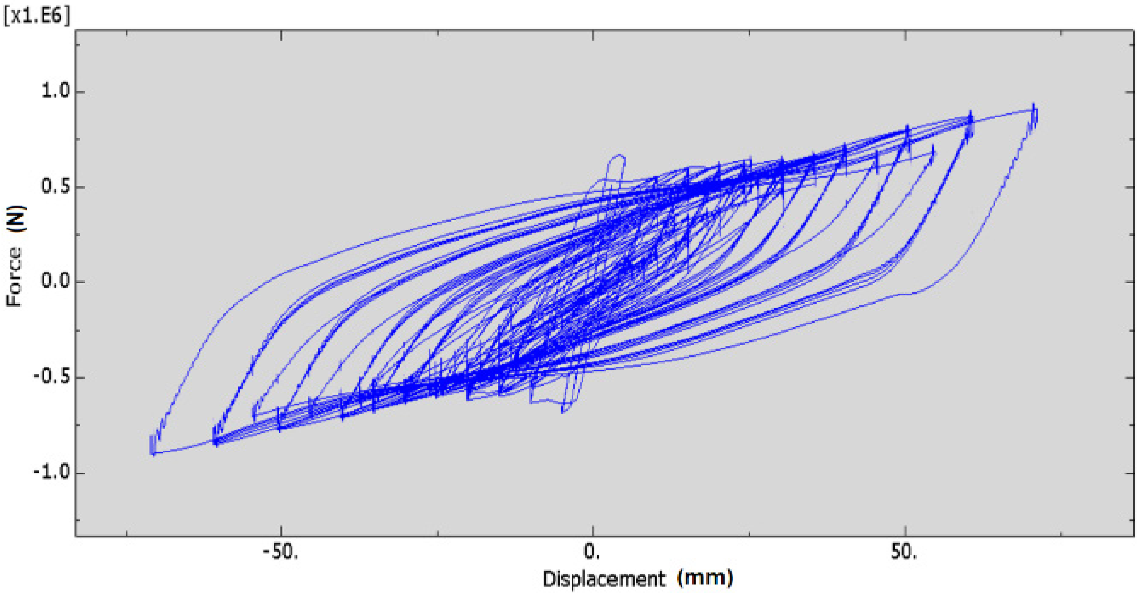


Figure 13. Hysteresis loops for FEM Model of DPSW

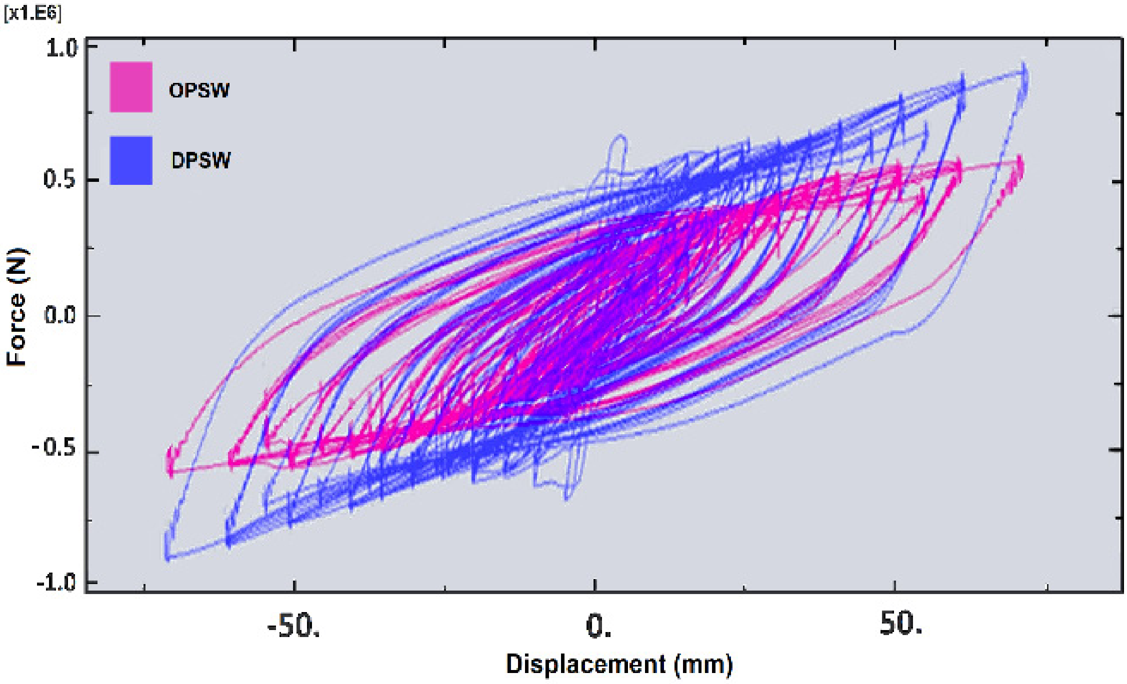


Figure 14. Superposition of Hysteresis loops between OPSW and DPSW Models

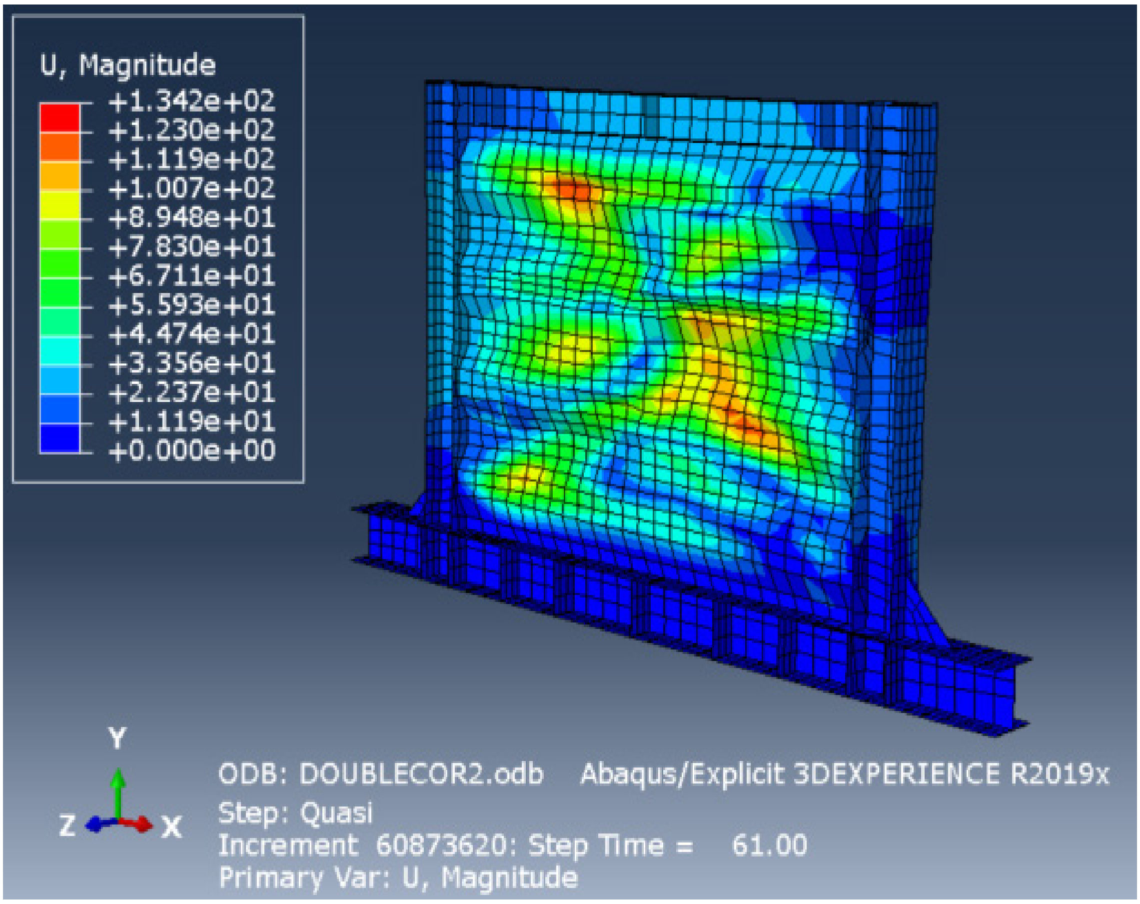


Figure 15. Inelastic Deformation at Cycle 61 for DPSW

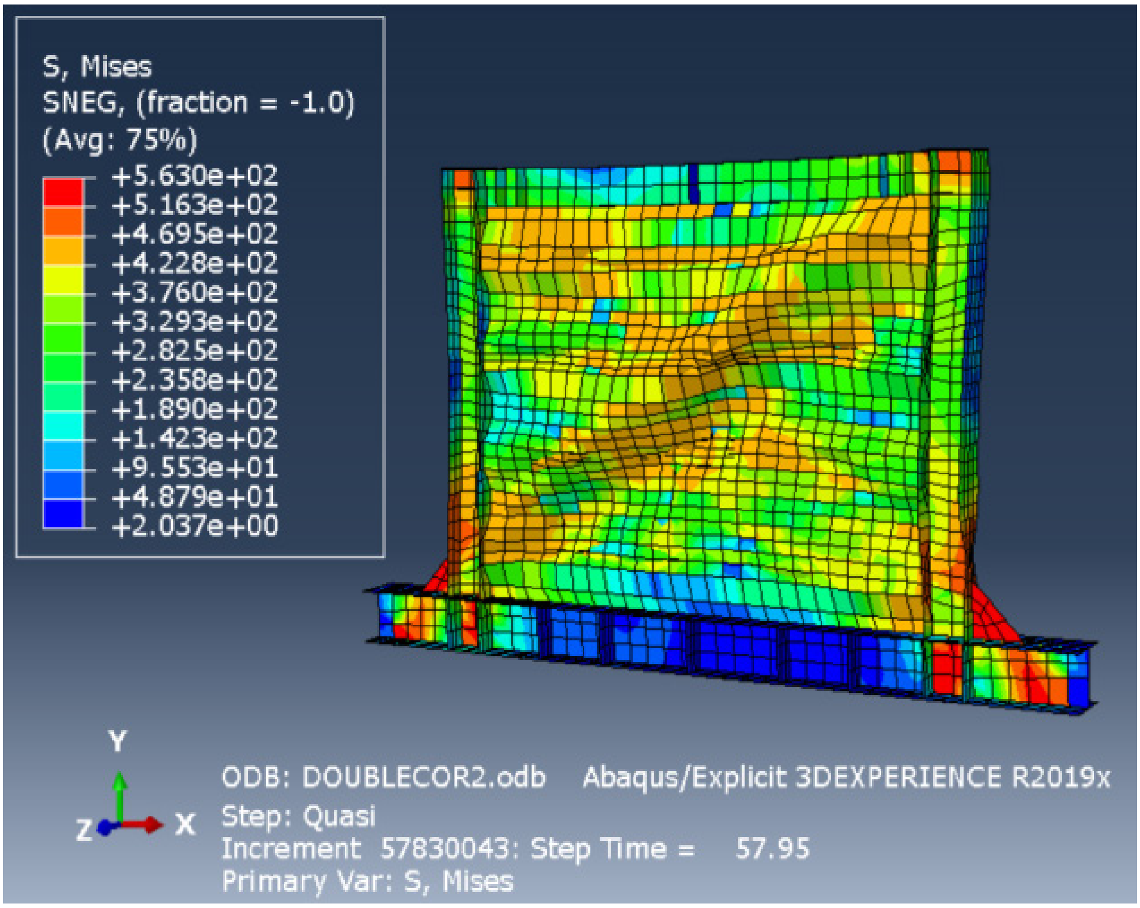


Figure 16. Von mises stresses at Cycle 58 for DPSW

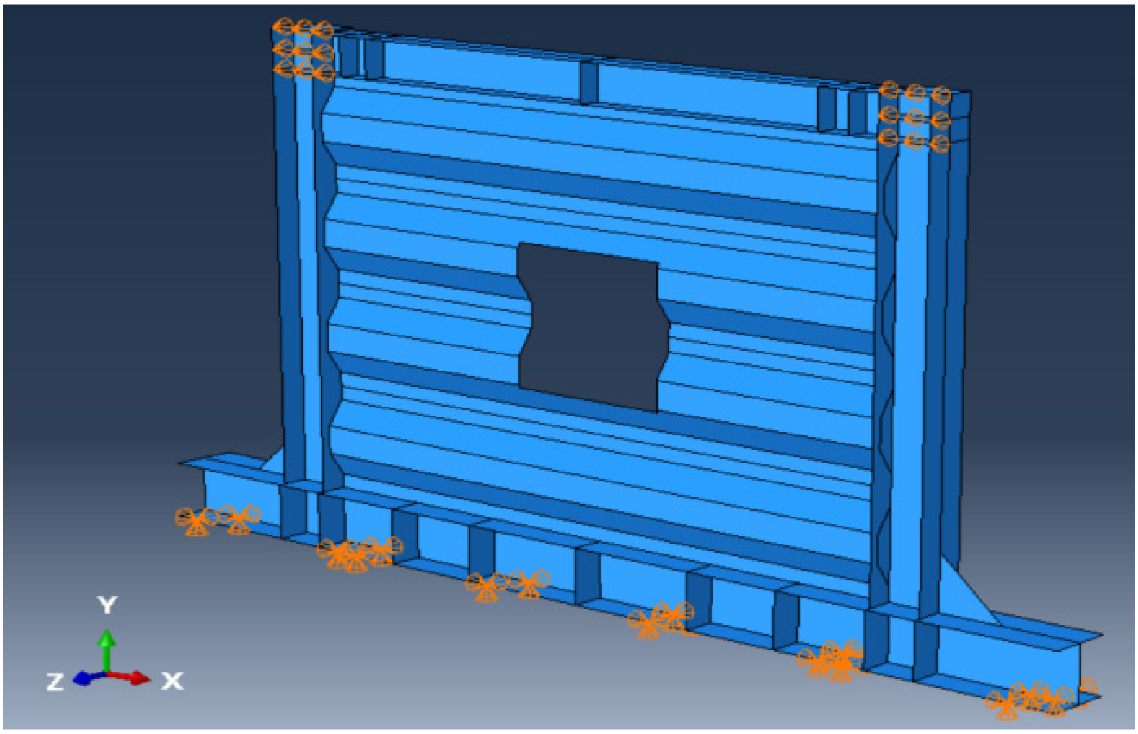


Figure 17. Finite Element Model of SOPSW

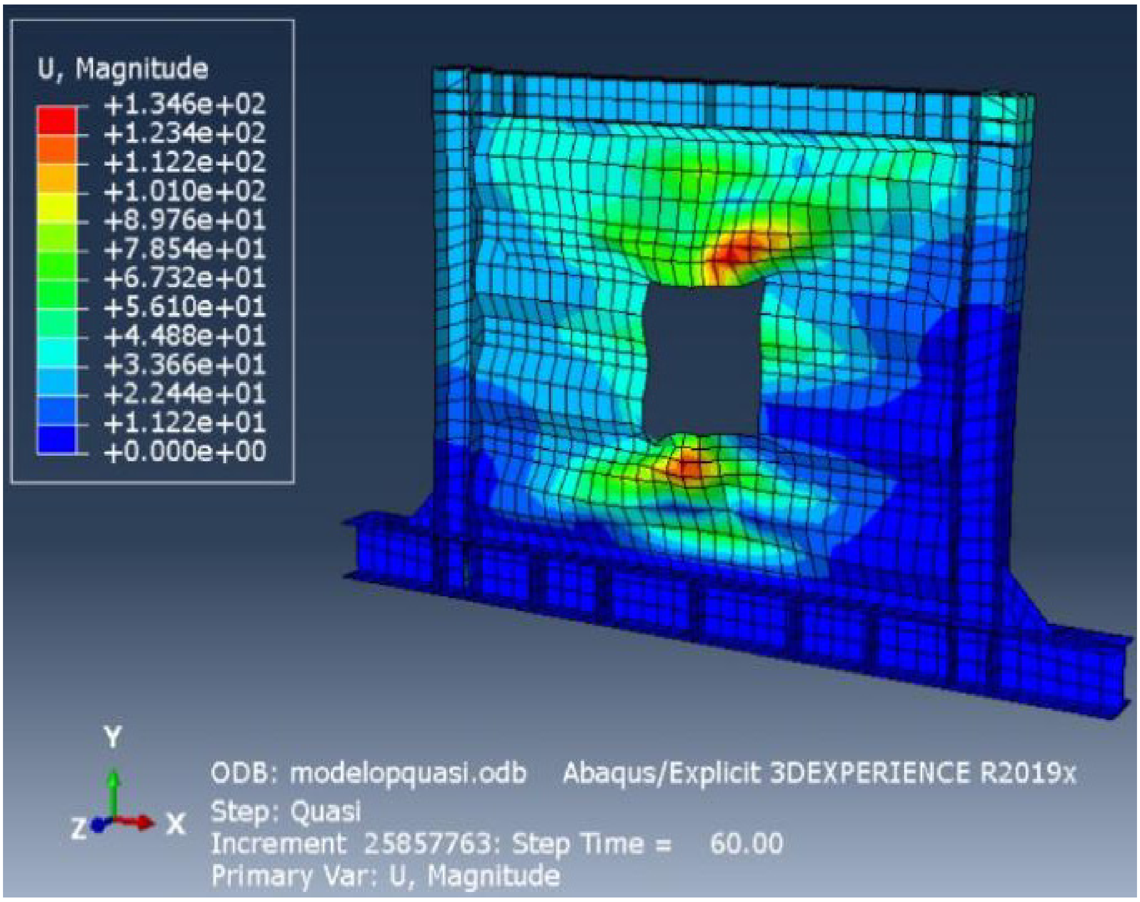


Figure 18. Inelastic Deformation at Cycle 60 of SOPSW

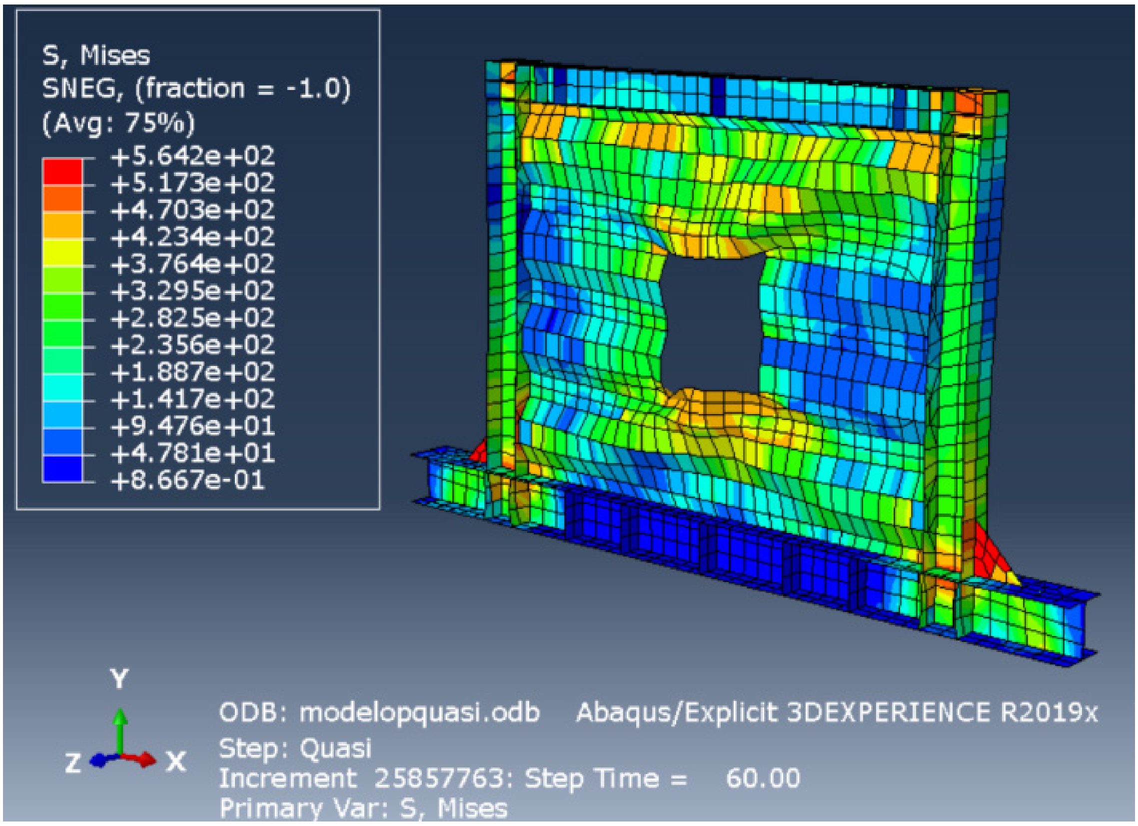
4.3. Horizontal Corrugated Steel Plate with Square Opening (SOPSW)

AISC 341-10 [9] permits the usage of web opening in special plate shear wall systems (SPSW) provided that they are bounded by intermediate boundary elements, extending the full width and height of the panel, unless otherwise justified by testing or analysis. In horizontal corrugated plates, providing the intermediate boundary elements is rather a difficult task. Thus, this study involves studying the effect of perforations on SOPSW without providing intermediate boundary elements to investigate the argument presented in the aforementioned AISC provisions.

Figure 17 illustrates the finite element model for SOPSW shear wall. A 500 mm square opening is provided in the middle of the plate. The ratio of $A_{hole} / A_{plate} = 0.085$.

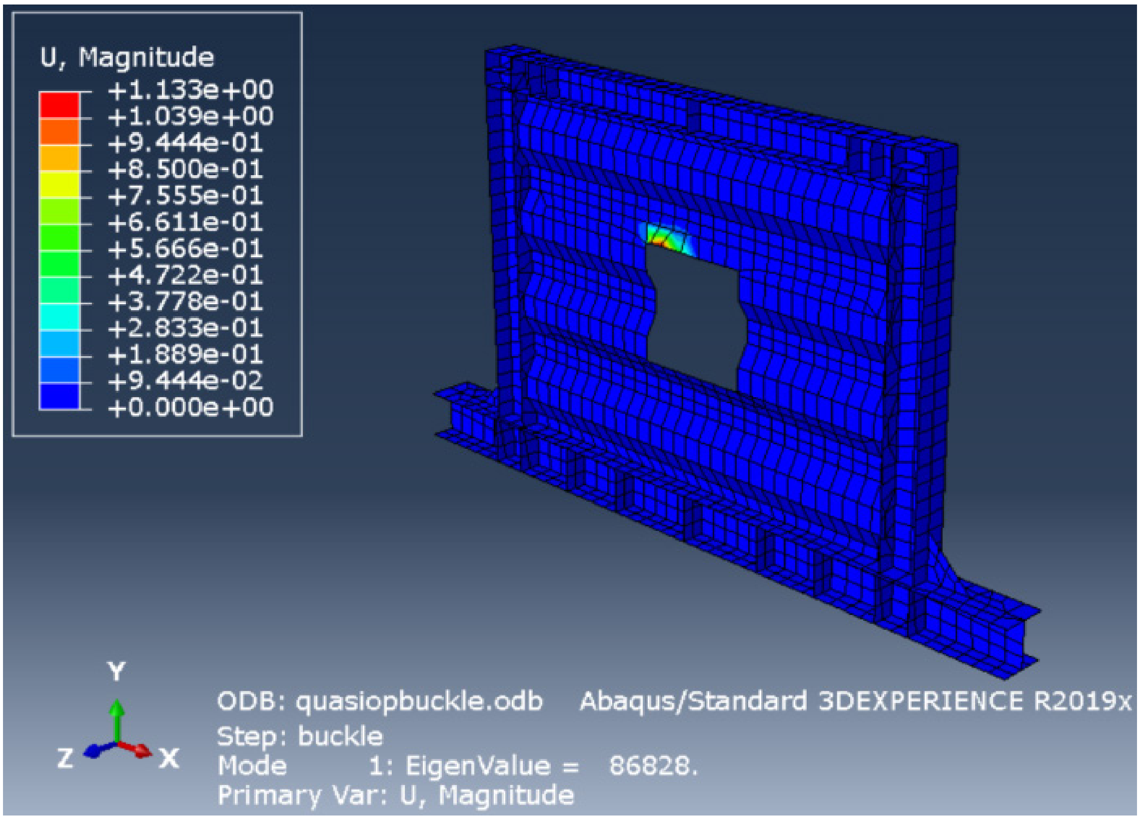
Figure 18 shows a localized plate buckling in SOPSW model at the top edge of the opening at cycle 60. Figure 19 illustrates Von Mises stress distribution of SOPSW model at cycle 60. It can be noticed that Von Mises (σ_{eq}) stresses are significantly lower in the vicinity of opening than in the regions that are away from the opening sides. This is attributed to the fact that large internal in-plane shear flow develops within regions of continuity in the plates owing to their relatively high shear rigidity compared to regions close to perforations of relatively less shear rigidity. This is similar to the concept of a moment resisting frame were high stresses develop at the rigid joint that connects the beam with the column.

The SOPSW shear wall experienced a 13 % reduction in the plate load carrying capacity compared to the OPSW Shear walls. Figures 19, 20 illustrate the development of plate local buckling at the perforation upper edge. Figure 21 indicates that the ductility of the SOPSW model is reduced compared to the corrugated unperforated OPSW Model.



ODB: modelopquasi.odb Abaqus/Explicit 3DEXPERIENCE R2019x
Step: Quasi
Increment 25857763: Step Time = 60.00
Primary Var: S, Mises

Figure 19. Von mises stresses distribution at Cycle 60 of SOPSW



ODB: quasiopbuckle.odb Abaqus/Standard 3DEXPERIENCE R2019x
Step: buckle
Mode 1: EigenValue = 86828.
Primary Var: U, Magnitude

Figure 20. First eigen buckling mode of SOPSW

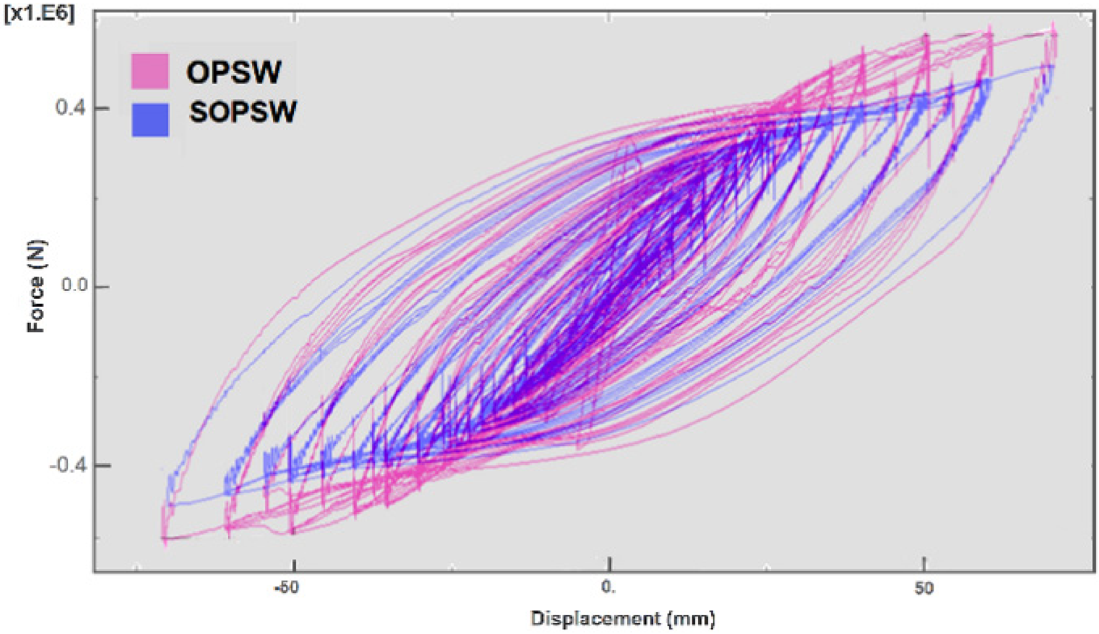


Figure 21. Superposition of Hysteresis loops for corrugated plates with and without square openings

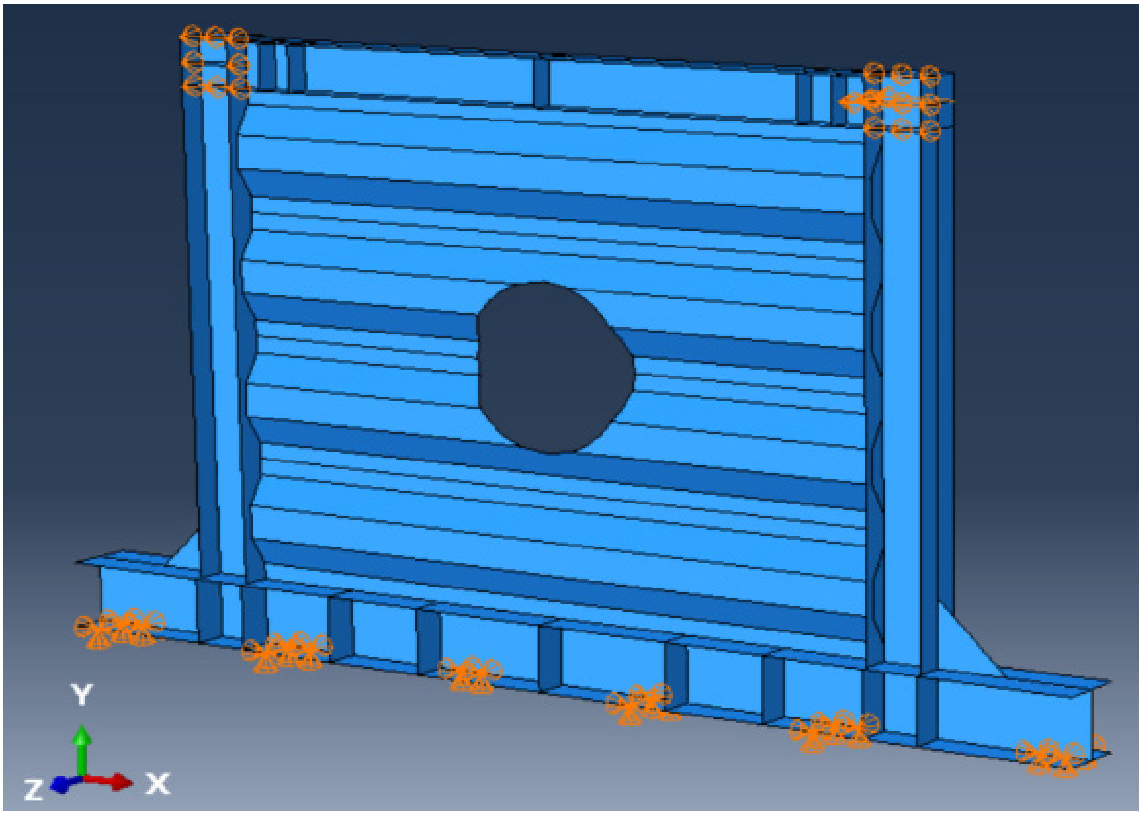


Figure 22. Finite element Model of COPSW

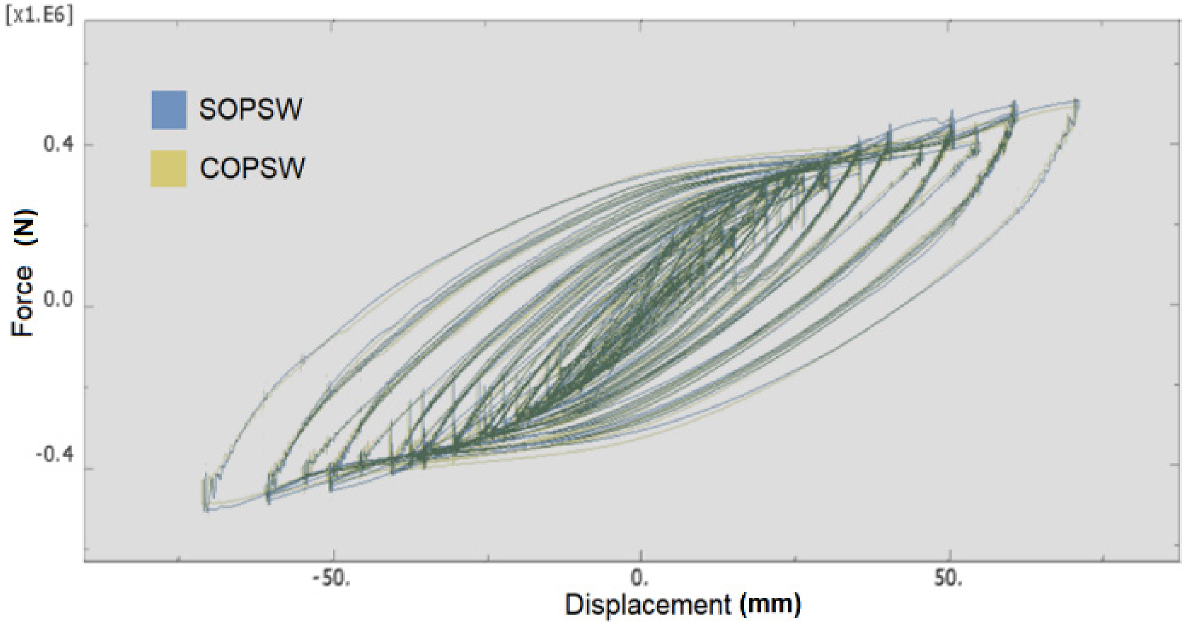


Figure 23. Superposition of Hysteresis loops for corrugated SOPSW & COPSW shear walls

4.4. Horizontal Trapezoidal Corrugated Steel Plate with Circular Opening (COPSW)

The circular perforation diameter is 500 mm, and it is located at the plate center of area.

Figure 22 illustrates the finite element model of COPSW.

Figure 23 illustrates the superposition of the hysteresis loops for both the corrugated square and circular perforated plates. The loops are very close to each other, indicating that the shape of the opening has a minor effect on seismic performance.

Figures 24, 25 indicate that the inelastic deformation as well as Von Mises (σ_{eq}) of the COPSW model at high loading cycles is considerably less in the plate with circular perforation than in the plate of square perforation. The largest deformation in COPSW model exists away from the vicinity of circular perforation, whereas the largest deformation in SOPSW model is close to the edges of the square perforations.

In addition to the higher elastic buckling strength in COPSW model compared to SOPSW model, it can be noticed that the inelastic deformation in the SOPSW model at high loading cycles is less than in the plate with circular opening as in COPSW model, where the zone with the highest deformation and Von Mises (σ_{eq}) stresses will not be near the opening, as opposed to what was observed in SOPSW model, (Figures 24, 25).

4.5. Increasing the Infill Plate Thickness Using (TPSW) Model

In order to investigate the effect of the corrugated plate thickness on the overall performance of the shear wall, the infill corrugated plate thickness was increased from 1.25 mm to 3.0 mm. Figure 26 illustrates the first Eigen buckling mode. Figure 27 illustrates the superposition of the hysteresis loops for TPSW and OPSW models. It indicates that the shear stiffness, strength capacity as well as ductility of the shear wall are significantly increased upon increasing the plate thickness.

Figure 28 illustrates Von Mises stress distribution along the plate at cycle 60 in TPSW model. Shear stiffness, strength capacity as well as ductility of the shear wall are significantly increased upon increasing the plate thickness. The improvement of the stiffness of the shear wall system leads to increase in the design demand on the vertical boundary elements connected to the corrugated plates.

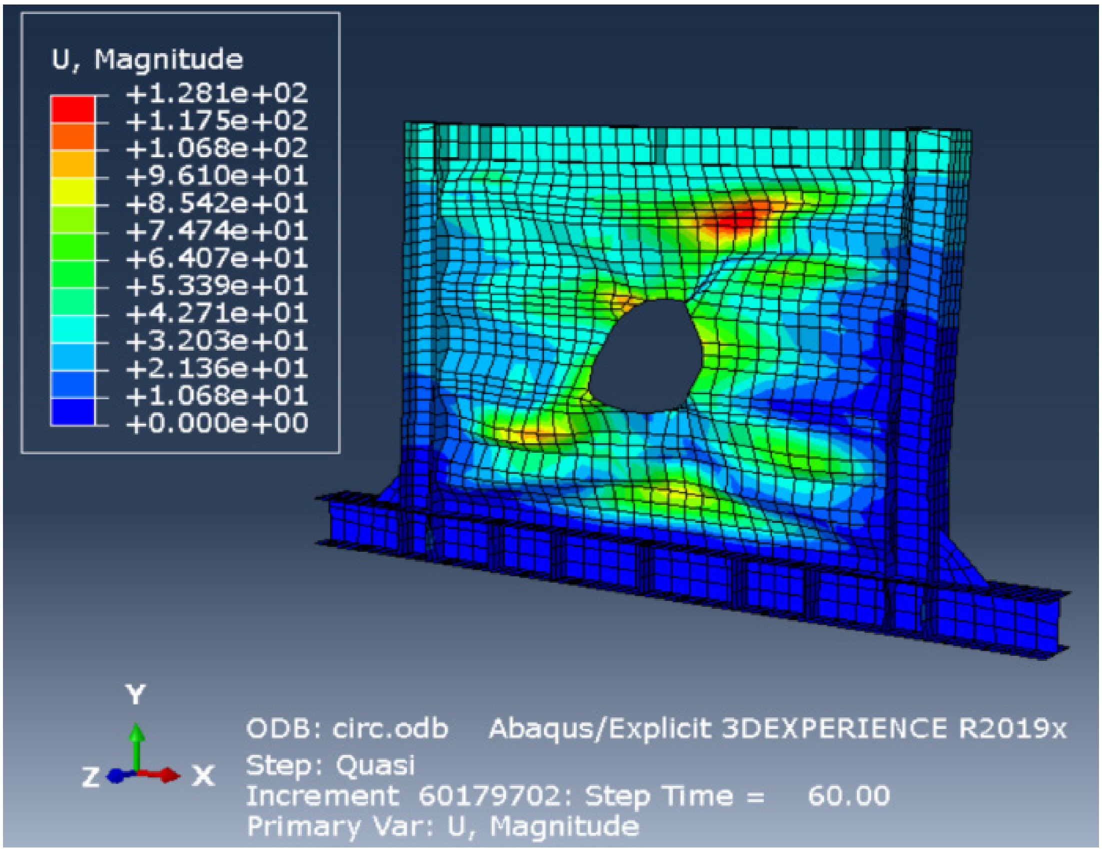


Figure 24. Inelastic Deformation at Cycle 60 for COPSW

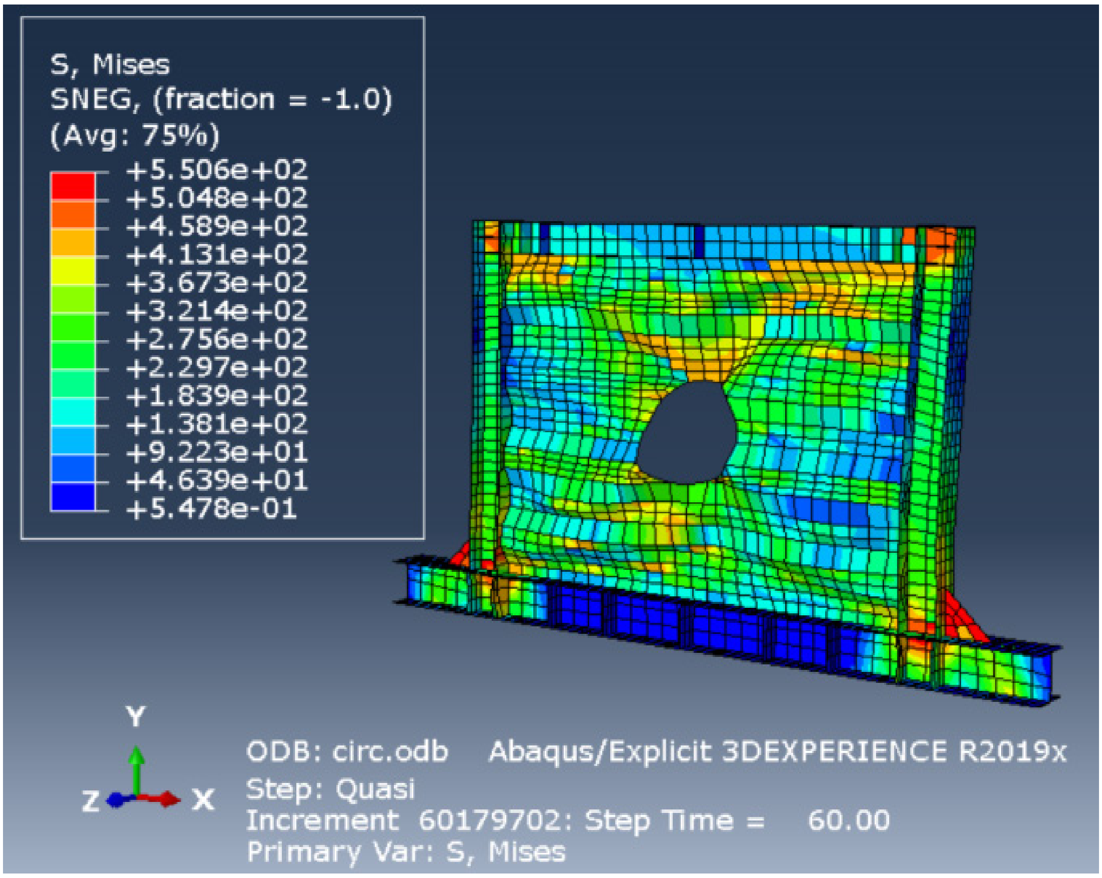


Figure 25. Von mises stresses at Cycle 60 for COPSW

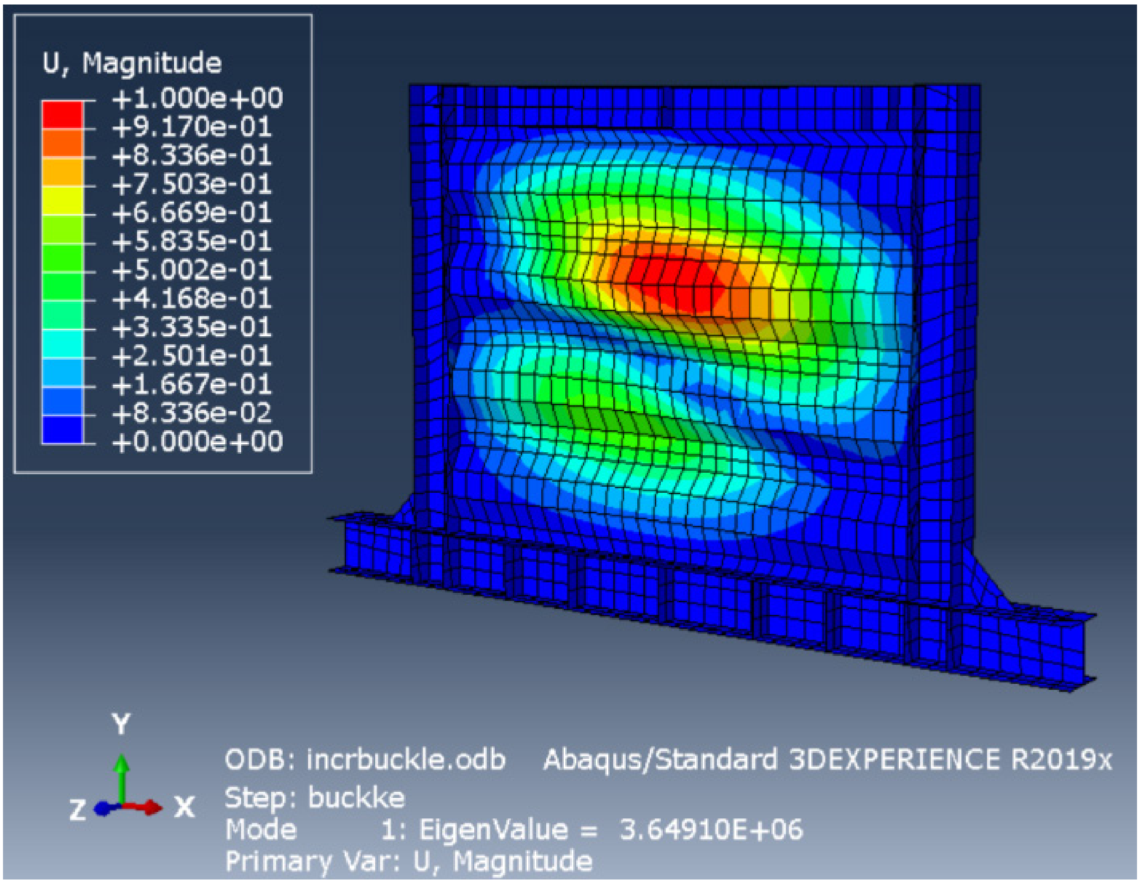


Figure 26. First eigen buckling mode of TPSW model

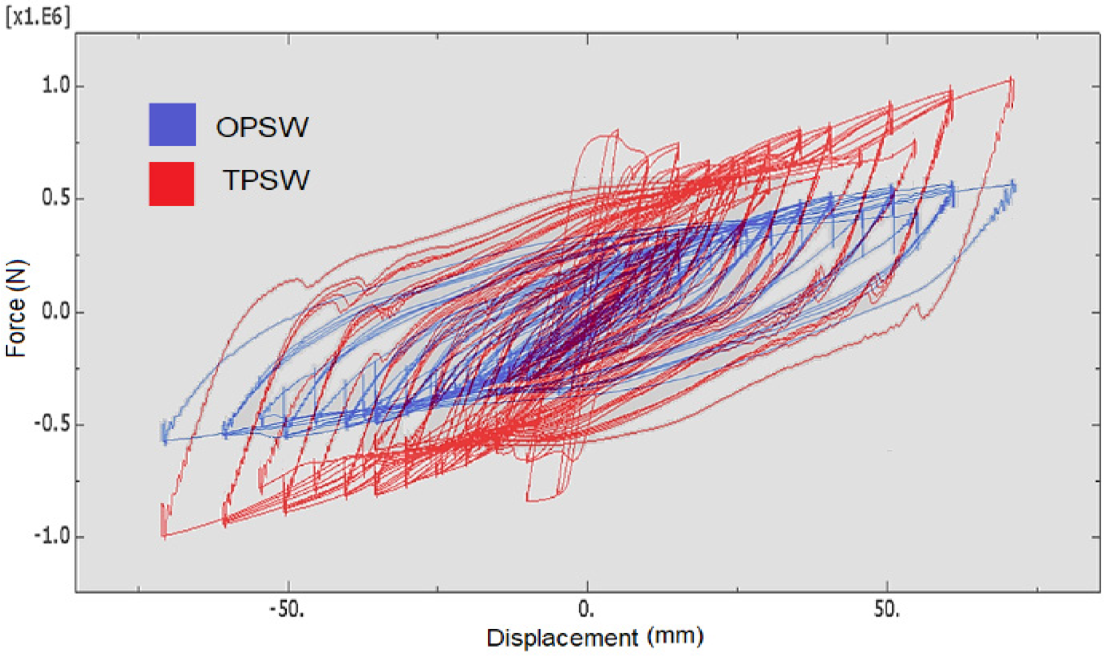


Figure 27. Superposition of Hysteresis loops between OPSW & TPSW models

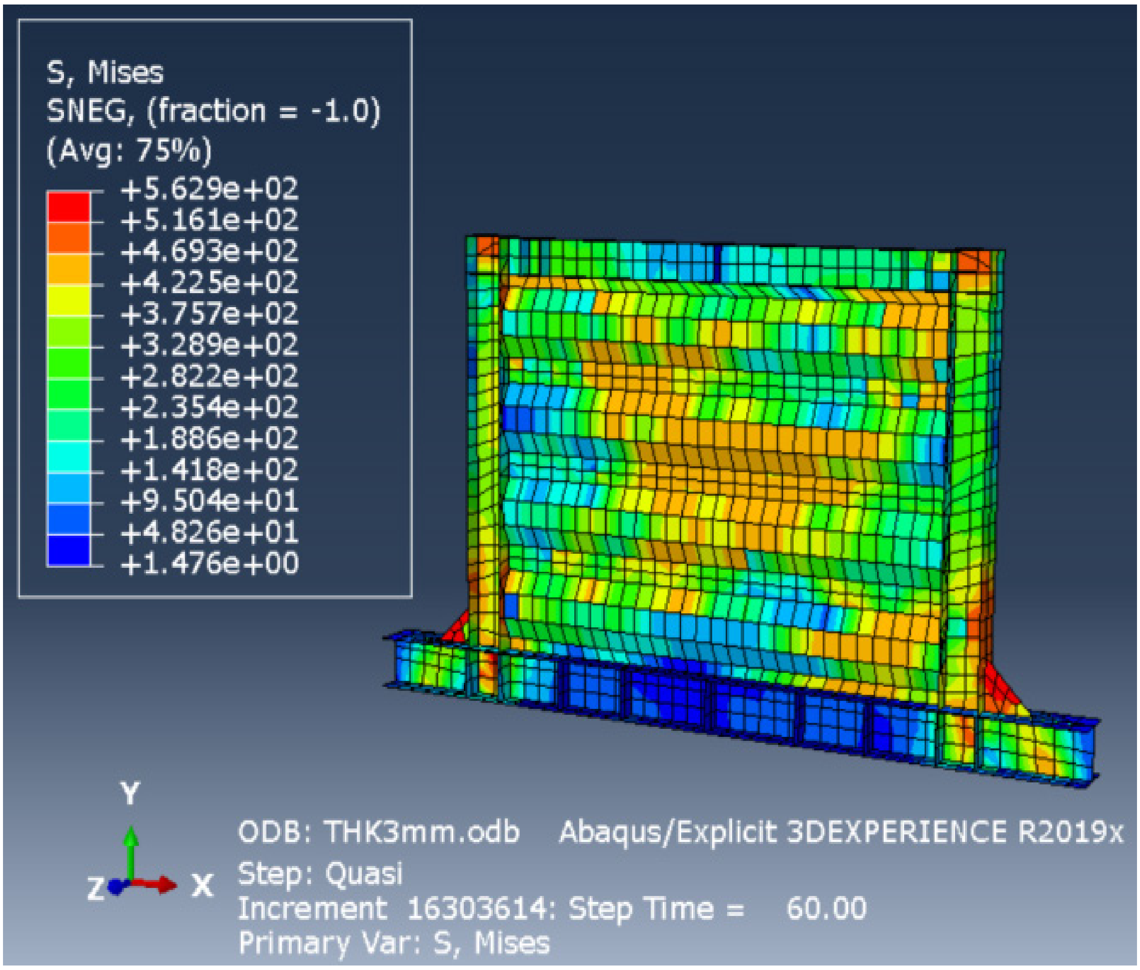


Figure 28. Von mises stresses at Cycle 60 for TPSW

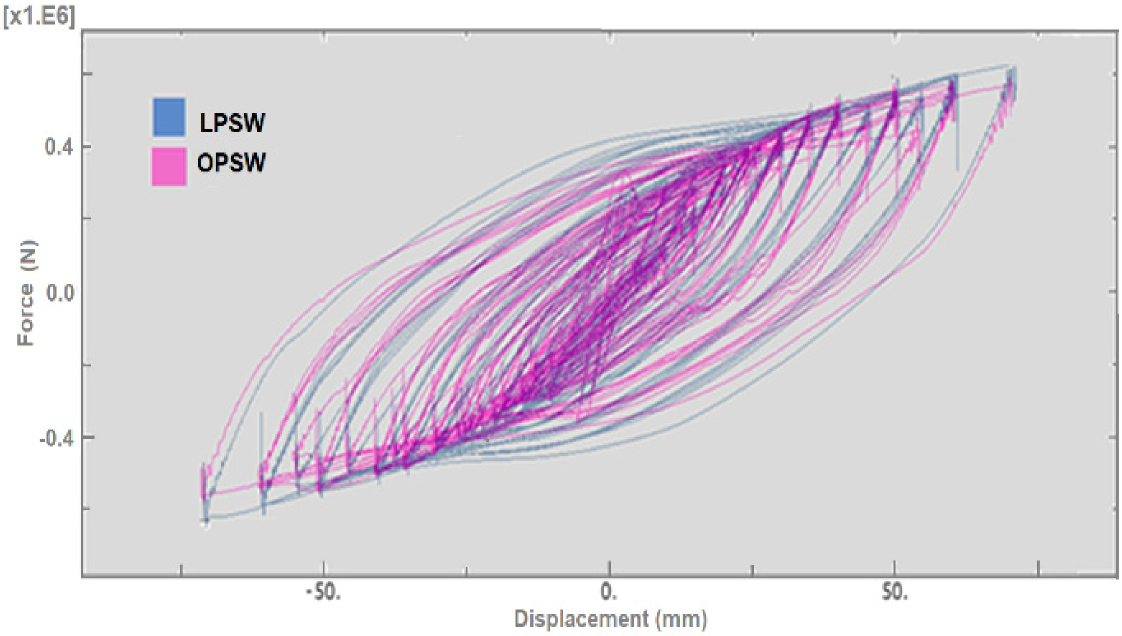


Figure 29. Superposition of Hysteresis loops upon reducing b/h ratio

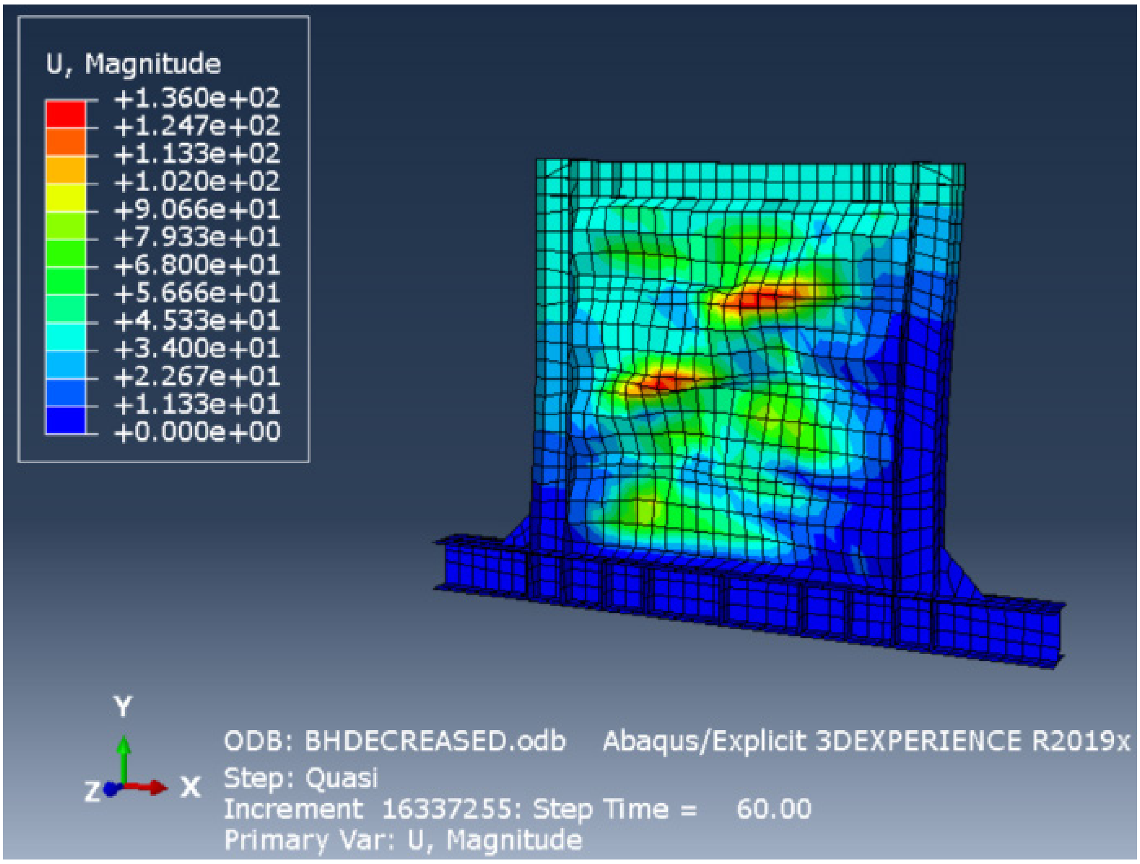


Figure 30. Inelastic deformation of LPSW at Cycle 60

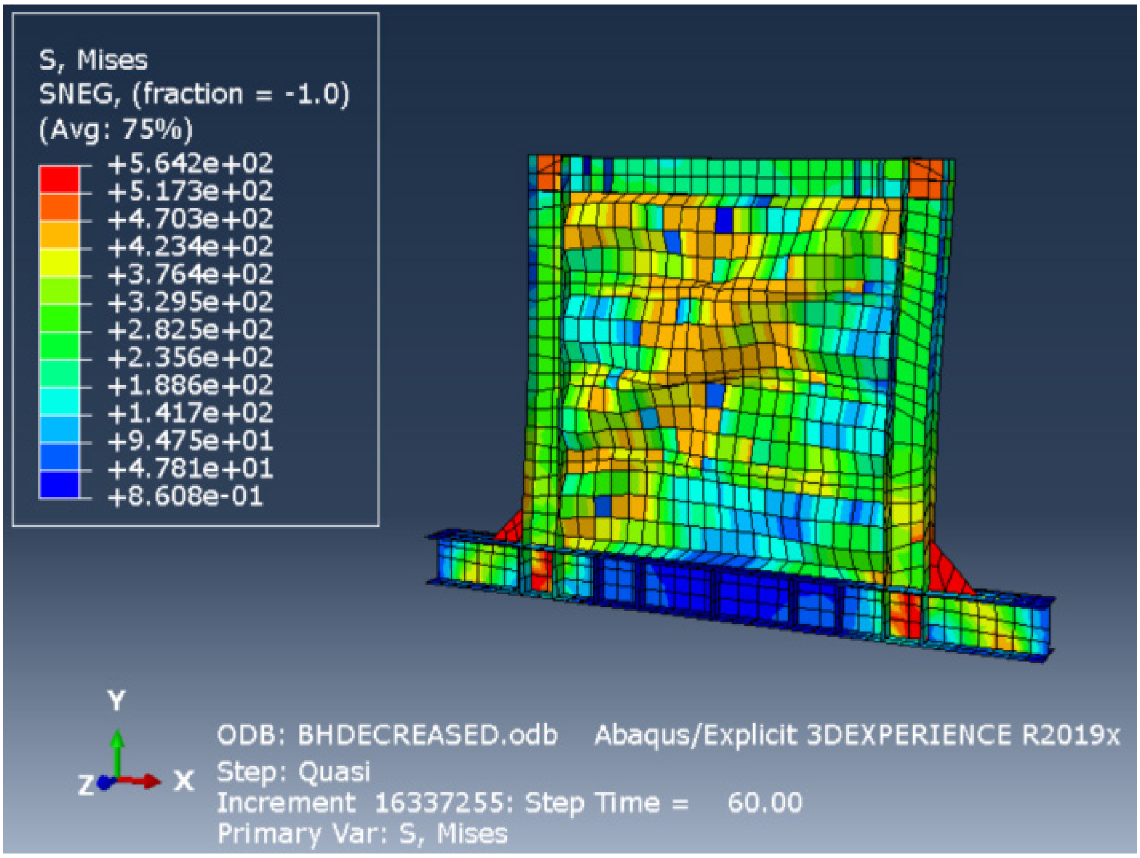


Figure 31. Von Mises stresses for LPSW at Cycle 60

4.6. Horizontal Corrugated Plate Shear Wall with Reduced b/h Ratio LPSW

In order to investigate the effect of the corrugated plate shear wall aspect ratio on the performance of the shear wall system, the aspect ratio of the infill plate was reduced from 1.34 to 1.0. Figure 29 illustrates the superposition of the hysteresis loops pertaining to OPSW model of b/h=1.34 and LPSW model of b/h = 1.0. Figure 29 indicates that the shear strength and energy dissipation of the shear wall were slightly increased when the aspect ratio was reduced. This is indicated in the larger enclosed area within the LSPW hysteresis loop compared to OPSW hysteresis loop.

Figure 30 illustrates the inelastic deformation for LPSW. It is slightly less than inelastic deformation for OPSW model. Figure 31 shows Von Mises (σ_{eq}) stress distribution in LPSW models at Cycle 60. It is also slightly more than Von Mises (σ_{eq}) stress distribution in OPSW models at Cycle 60.

5. Conclusions

Nonlinear push over and cyclic finite element analyses were carried out to study the different forms and configurations of horizontal trapezoidal corrugated steel plate shear walls, namely singly corrugated, doubly corrugated as well as perforated corrugated steel plate shear walls. Based on the results of finite element analysis and the parametric study, the following conclusions are presented:

- Increasing the corrugation depth enhanced the initial elastic stiffness, the critical buckling load, the ductility, as well as the ultimate lateral strength and the residual strength of the horizontal corrugated plate shear wall. In this case the reduction in out of plane deformation was around 20%.
- Using double corrugated plate shear walls improved the strength capacity of the horizontal corrugated plate shear wall by about 38%.
- The double corrugated steel plate shear wall system is an efficient and cost-effective structural solution in resisting earthquake action. It has enhanced initial elastic stiffness, as well as buckling strength that paves the way towards high ultimate strength capacity. The double corrugated steel plate shear wall system also exhibits large ductility and experiences energy dissipation owing to its capacity to develop internal inelastic strains and stresses beyond the steel energy density, leading to low base shear values.
- In the case of perforated plates. The corrugated steel wall with circular opening experienced a tangibly higher buckling strength. Sharp edges in square openings considerably diminish the corrugated plate buckling strength.
- Perforations reduce the contribution of the plate in resisting the seismic forces, as well as the subsequent reduction of the corrugated plate shear wall strength and stiffness.
- Providing a square or rectangular perforation without adding stiffeners at the edge of the perforations significantly reduce the corrugated plate initial elastic stiffness. The plate may experience elastic buckling at relatively low load values.
- On the other hand, providing a circular perforation without adding stiffeners at the edge of the perforation will not result in degrading the initial elastic buckling strength.

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