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# NUMERICAL STUDY ON STIFFENED STEEL PLATE SHEAR WALLS WITH CENTRAL PERFORATION

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***Abstract.*** *Nowadays One of the advantages of Steel Plate Shear Walls (SPSWs) is the easiness of openings application in infill plate. The openings are sometimes required for passing utilities, architectural purposes, and structural reasons.*

*More energy absorption and high load carrying capacity and post-buckling behavior of steel walls in the nonlinear behavior of this system has been more substantial than other bracing systems. Great stiffness than the bracing systems, the ability to create opening anywhere in the wall, the possibility of building in the factory and installing it in the place in any weather conditions, a 50 percent reduction in the steel consumption in the design of steel moment frames, speeding up the implementation of the designed or retrofitted projects and reducing the cost of the design and retrofitting, especially in retrofitting the concrete structures are the main advantages of that. Different regulations, including the regulation of designing the steel structures of Canada and 450 FEMA have provided some criteria for designing steel plate shear walls. In 2005, the rules governing to designing of special steel shear wall has been added to the regulation of seismic designing of AISC Steel Structures. In this article it has been tried to acquire the similar behavior of the steel shear walls without opening by installing the stiffness in the place and with the appropriate form on the steel shear walls with openings. For this purpose, the verification of the results of the numerical analysis was done with a laboratory model from the researches of Mr. Alavi and Nategh Elahi in 2013. Then, according to the previous studies, seven models with a scale of one to seven, and the ratio of width to thickness 500, that had higher amount of energy absorption, were selected with perforations by 0% , 20% and 35% ratio and the different models of shape and stiffeners location were loaded reciprocally.*

*According to the obtained results from the analysis of the numerical models under the reciprocal dynamic load and the investigation of the obtained pushover charts and the comparison of the seismic parameters such as strength, stiffness, ductility and also energy*


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*absorption of panels, it was observed that the sample with a rhombus stiffener has the similar behavior to the shear walls without a stiffener up to the rupture creation level.*

## INTRODUCTION

According to the huge human and financial losses that occur each year due to the wind and earthquake forces, the researchers have been trying to achieve a suitable structural system with the minimal losses. Nowadays, there are different kinds of structural systems resistant to the lateral loads that among them, buckling frames, bracing systems and concrete and steel shear walls can be mentioned. In the last three decades, there has been wide interest and attention in the use of steel shear walls as the resisting system against the lateral load in the buildings. Steel shear wall is such a steel plate beam that is placed vertically and extends the entire height of the building. A relatively thin steel plate connected to the beams and columns, behaves like the web of a plate beam. Columns and horizontal beams play the role of the wings and the stiffeners of the vertical plate beam. Although it seems that plate beam theory is appropriate for designing a steel shear wall or simply SPSWS, there is a substantial difference regarding the relatively high flexural strength and the stiffness of beams and columns that make the wall boundary elements toward the plate beams. It seems that these elements have a significant effect on the overall behavior of buildings. The advantage of this system compared to the other structural systems resistant to the lateral forces has led to the increase use of it day-by-day. The use of steel shear wall is an effective method to increase the stiffness and strength without increasing the weight of the structure and in comparison with the moment frame system, it almost saves fifty percent of the steel consumption. Some engineers believed that the sheets should not be allowed to buckle. This topic created two mindset. In Japan, thin sheets were considered by closely spaced stiffeners, while in America thick sheets were used. In the structural design, supplying of the interior appropriate space is the most important design goal. Simultaneous with the interior space finding, architects are required to satisfy the demands of the employers and beneficiaries of the building and also create the appropriate view. Therefore the primary criterion of the design can be related to its architecture then after that, the engineer will be bound to creating the appropriate structures within the designated spaces. Just about the long and important structures, the building structure and the conditions and restrictions of engineering as the designing primary criteria are replaced with some architectural needs. Applying such architectural needs and beautification can be considered as an important factor of creating the perforation in the steel shear walls. As well as, the building structure must be coordinated with serviced systems such as mechanical and electrical installation, water and sewer that are a complex and bulky set that allocate a large share of the structure investment, especially high-rise buildings to themselves. So non-structural considerations such as the position and the direction of installation systems can be other effective factors of creating the perforation in the steel shear walls. Compared to the conventional bracing systems, the continuity of the steel panels lead to the creation of the formable behavior and the stability of the system under the reciprocating loading [7]. In addition, the great stiffness of the plates acts like the stretching anchors to maintain the stability. As SPSWs system is effectively introduced for energy absorbing systems in the areas with high seismic risk. Kulak at the University of Alberta was one of the first researchers that precisely examined the behavior of SPSWs [8]. Around 1980, his group performed two analytical and laboratory researches in order to develop the processes of proper design. Their results created a simple method for analyzing a thin unreinforced SPSWS (strip model). In that study the plate was replaced with a series of parallel diagonal stripe elements that are only able to transfer tensile force. The research that carried out by Rezai and colleagues [9] at Brithish Columbia University, it has been showed that the strip model for a wide range of SPSWS is fundamentally incompatible and does not predict the structural behavior accurately enough. They proposed a new analytical model named multi-angle strip model. However the multi-stripe model did not have a high precision and further research in this area had been proposed. The conducted researches show that the steel shear walls with thin plate and without web stiffness which is also called particular steel shear wall, has a good performance in terms of economics and efficiency in tolerance of lateral loads. Design regulations including AISC341 [6] recommended the use of this lateral loading system in the areas with the medium and high seismic risk. The difference is that, in the areas with high seismic risk, it's necessary that the beam connection to the column be able to withstand and transmit the flexural strength.

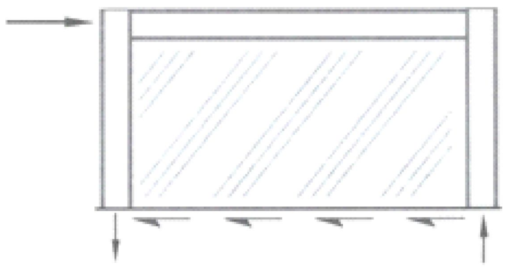

Figure 1: The ideal behavior of shear walls

In the steel shear wall system without web stiffness, the pressure capacity of web plate is very small but tensile strength of the web plate that comes with the experience of large Ultra-elasticity deformations is high. The behavior of shear walls without stiffness web plate can be simulated with a bracing frame that the diameter components of it just work to stretch. The overturning forces can be tolerated by columns and through the bracing vertical component. The beams are under the huge pressure thrust forces resulting from the horizontal elements of braces. This behavior can be simulated by the performance of a plate beam with thin web in which the beams are like the middle strengthening, columns are like the wing of plate beam and the fillers plate of wall is like the web. By comparing the behavior of steel shear wall with the plate beam, this point can be realized that the wings in the plate beam do not provide the sufficient stiffness to develop the tensile field in the web of plate beam; However, the vertical boundary components in the steel shear walls provide the sufficient rigidity to create the tensile field in the web plate. The vertical and horizontal boundary elements in the steel shear walls are under the influence of wide forces in their length due to the tensile performance of the filler plate of shear wall. Tensile forces in the horizontal boundary elements of the steel shear walls due to the performance of the web plate above and below the horizontal boundary elements neutralize each other to some extent. The web plates in the steel shear walls create considerable tensile forces on the first and last floor at the level of the top floor (roof) and the downstairs (the foundation) that it is necessary to be properly tolerated by the horizontal boundary elements. So the dimensions of the beams will be substantially at the roof level and these forces must be restrained by the steel or concrete horizontal beams at the floor level too. If the flexural rigidity of the column and in other words its moment of inertia around the flexure is not enough, in this case, the possibility of the development of the tensile field in the plate web will not be possible and the system resistance will be significantly reduced. If the column stiffness is suitable and sufficient, then the possibility of developing the tensile field in the web plate will be provided. The shear force due to the tension field in the web plate in the columns of both sides of web are in opposite direction of each other and the horizontal reaction of the column support under the pressure is in the opposite direction of the horizontal reaction of web plate.

## THE STIFFNESS AND STRENGTH AND ENERGY ABSORPTION

Two determining factors in systems resistant to lateral loads such as bracing systems, steel shear walls, moment frames, concrete shear walls and etc. are their stiffness and strength that their lateral location is determined by load-shift diagram. An example of these diagrams is shown in a general image in the figure 2. In the mentioned diagram the line slope of OA is called the stiffness of resistant system and Fu is the resistance or ultimate load of the system. As it can be seen in the figure, the relationship between load and lateral displacement in elastic environment is as follows:

$$F=KU \tag{1}$$

For determining the stiffness of system in any alignment, above equation can be used. Systems that have more stiffness, their lateral displacement is lower against the lateral loads.

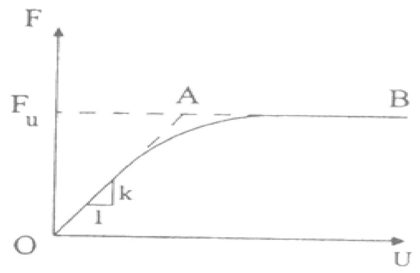


Figure 2: load-displacement diagram

In the case of the significant displacement of the structure and thus the large deformation, non-structural elements such as doors, elevators, blades, views, infilled frames and especially installations may cause serious flaws. In some special buildings such as hospitals, museums, laboratories, etc. in which sensitive equipment is placed, numerous displacements can cause irreparable damages that makes the use of resistant system with great stiffness required. Although scientists generally believe that the acceleration is the most important parameter of how individuals respond to vibration and it may create a variety of adverse reactions such as nausea and anxiety for residents of the buildings, especially tall buildings and causes discomfort for them, But large displacements can also cause the insecurity, especially in earthquake that compared to wind fluctuations occurs less and the vibration time is usually short-term, but its movements are strong. Thus the design criteria in the earthquake will be safety before the comfort that is usually in conjunction with the wind. As it can be seen in the hysteresis curves related to the steel shear walls, these curves are S-shaped and are quite stable and the rate of energy absorption of the mentioned system that in fact is the area under hysteresis curve is significant. Also by increasing the displacement in each cycle, the area under hysteresis curve shows an increasing compared to the previous cycle. To improve the hysteresis curves and increase energy absorption rate (increase the area under hysteresis curves) in the steel shear walls can operate in two ways:

• Increasing the thickness of the steel plate
• Reinforcing the steel plate by stiffeners

The first solution is totally uneconomical and expensive, because for improving the hysteresis curves of the mentioned walls, it is necessary to increase the thickness of steel plate enough until the plate does not buckle before yielding that this thickness increase is quite substantial and hence uneconomical. The second solution that can be achieved through reinforcing the steel plate by stiffeners is more efficient and economic. In the experiments that were done by Takahashi and colleagues on a number of steel shear panels with plates with different thicknesses and stiffeners with different dimensions, spacing and arrangement, it has been shown that by effective reinforcing of the steel plate, we can reform the hysteresis curves in the steel shear walls from S-shaped to fusiform and thus by increasing the area under the mentioned curves increase the rate of energy absorption and improve the behavior of the walls.

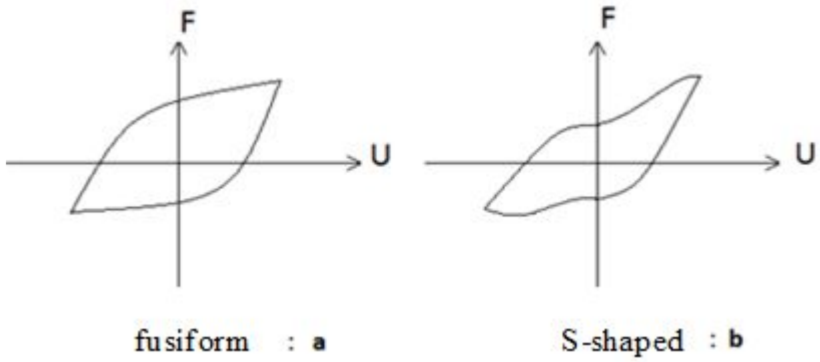


Figure 3: load-displacement diagram

**VERIFICATION**

To obtain an analytical model that is consistent with the acceptable accuracy with the laboratory sample, several analyzes were done. The investigated laboratory sample was the shear wall that reviewed by Mr. Alavi and nateghi (Alavi 2013: 9). The investigated shear wall has been brought in Figure 3. The final load-displacement responses of the laboratory samples and the results of the analysis are shown in Figure 5. The name of the shear wall without a stiffener in the research was SPSW (s1). Steel type ST-37 is used to make the samples. Beams and columns were considered from HEB160 and the thickness of shear wall plate was 1 mm and the thickness of the amplifier inside the beam and column was 5 mm. The profile of the consuming materials for constructing the beam, column, shear wall and stiffeners have been shown in table 1. The steel shear wall with four-node shell elements

(S4R) was reduced by integration and the formulation of large deformations has been modeled. Using this formulated method reduces the analysis time. The stiffeners have been also modeled by using the shell elements. Bilinear equation is used to model the behavior of fine steel.

Table 1: The profile of the consuming materials [8],

| Steel material | Elastic modulus (MPa) | Static yield (MPa) | Static ultimate (MPa) | Yield strain (%) | Hardening strain (%) | Ultimate strain (%) | Rupture strain (%) |
|---|---|---|---|---|---|---|---|
| HEB160 (SPSW(s1,s4) | 2.06E+05 | 340 | 450 | 0.17 | 1.8 | 14.4 | 16.2 |
| HEB160 (SPSW2) | 2.07E+05 | 400 | 450 | 0.19 | 2.7 | 13.2 | 15.1 |
| Plate (THK. = 5 mm) | 2.05E+05 | 340 | 470 | 0.17 | 3.06 | 20.5 | 22.3 |
| Plate (THK. = 4 mm) | 2.05E+05 | 460 | 550 | 0.22 | 2.67 | 19.1 | 20.8 |
| Plate(THK. = 0.8 & 1 mm) | 2.04E+05 | 280 | 500 | 0.14 | 0.3 | 21.6 | 27.0 |

Figure 4: A picture of the shear wall studied in the laboratory (Alavi 2013: 9),

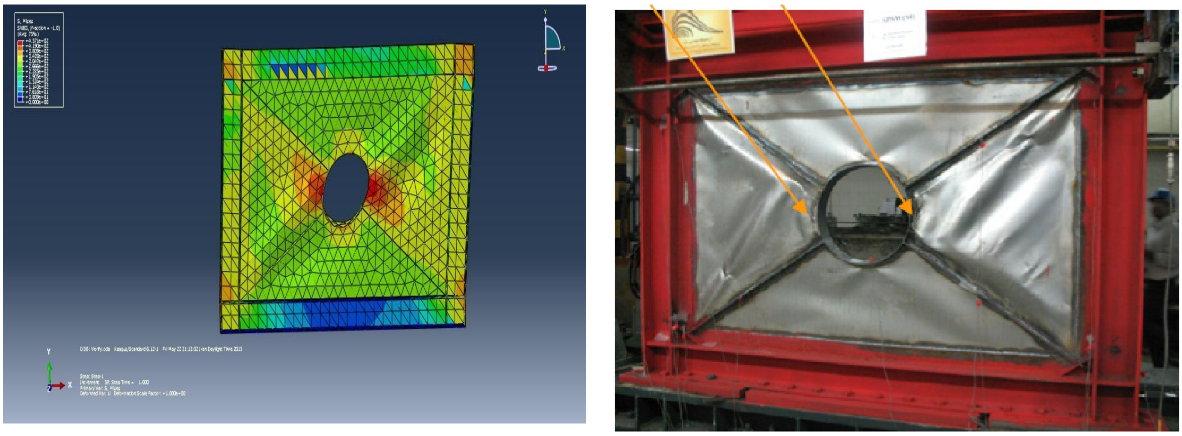

Figure 5: The laboratory and software figure of shear wall after buckling (Alavi 2013: 9),

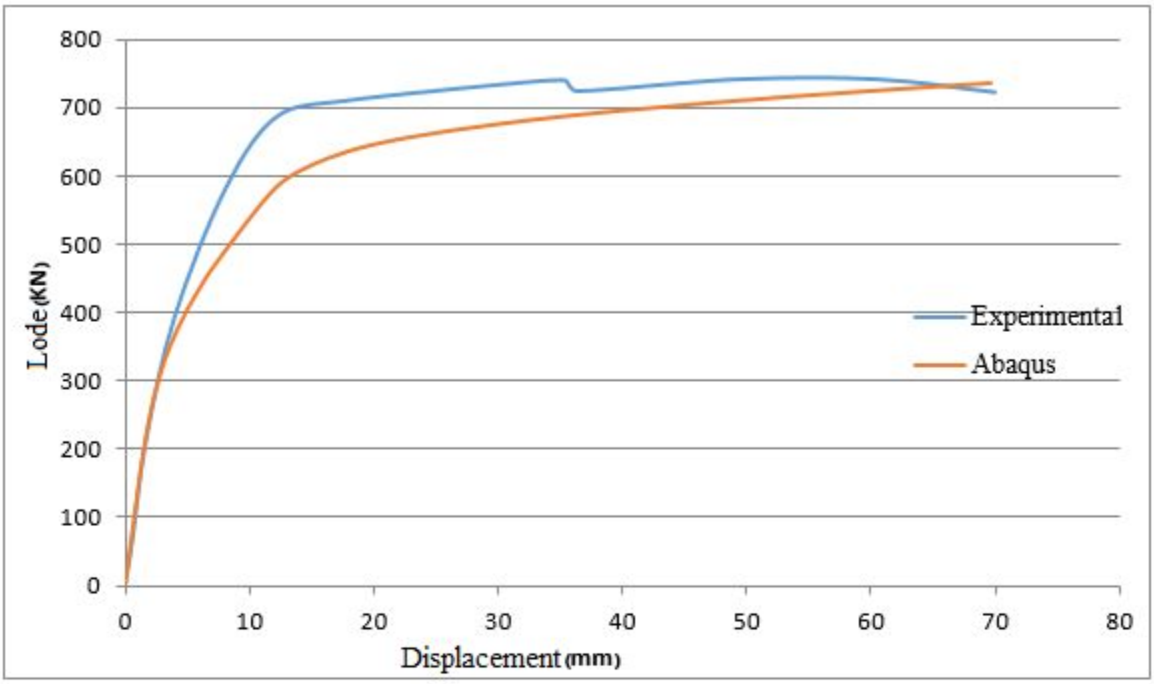


Figure 6: comparing the laboratory and software of the load-displacement diagram

After ensuring the accuracy of the analysis results in ABAQUS, analytical samples were defined and modeled.

## MODELING

Seven number of models with openings with the rate of 0%, 20% and 35% are modeled that their profiles are shown in Table 2. To investigate the effect of stiffener on shear walls with openings, two types of stiffener were used that the stiffeners are placed horizontally and vertically around the opening and are extended up to the horizontal and vertical boundary elements.

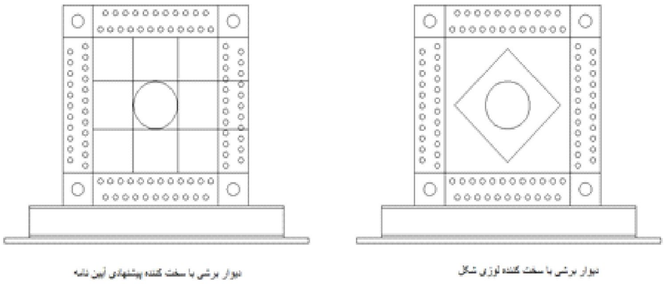


Figure 7: The way of connecting the stiffeners

The rhombus -shaped stiffener is used according to the Figure 7 and other samples with the proposed profiles of regulation are modeled.

Table 2: The profile of the modeled samples

| sample | Opening ratio ((percent | The type of stiffener |
|---|---|---|
| SPSWS1 | 0 | Without stiffener |
| SPSWS2 | 20 | Without stiffener |
| SPSWS3 | 20 | rhombus -shaped stiffener |
| SPSWS4 | 20 | Regulation stiffener |
| SPSWS5 | 35 | Without stiffener |
| SPSWS6 | 35 | rhombus -shaped stiffener |
| SPSWS7 | 35 | Regulation stiffener |

(All samples have the thickness of 1 mm and slenderness ratio of 500)

The material profile has been shown in Table 3.

Table 3: The profile of materials

| $F_y$ $(Mpa)$ | $F_u$ $(Mpa)$ | E $(Gpa)$ | $\upsilon$ | $\rho$ **(Kg/m3)** |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| 200 | 300 | 200 | 0.3 | **7850** |

5- Results analysis

Graphical output and the results of the models analysis due to the reciprocating loading have been shown in Figures 8 to 13. And the analytical results of the samples that have annular stiffener, annular and perpendicular to each other and annular and crisscross have been brought in the diagram of figure 14 based on the load to goal displacement.

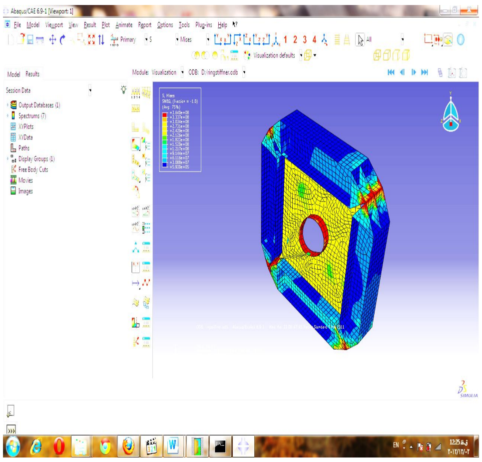

Figure 8: Shear wall with opening round annular stiffener

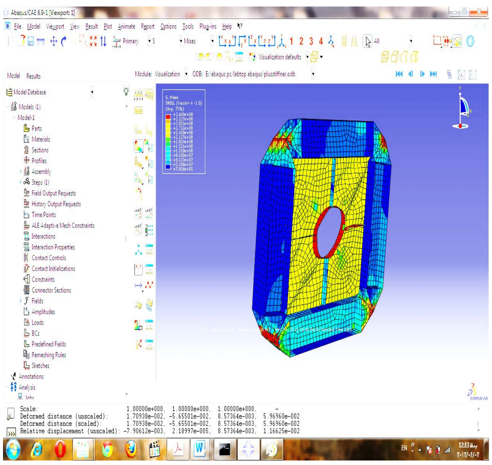

Figure 9: Shear wall with opening round stiffener and perpendicular to each other

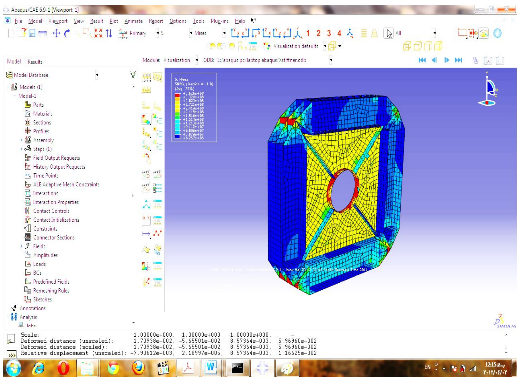

Figure 10: Shear wall with opening round stiffener and crisscross stiffener

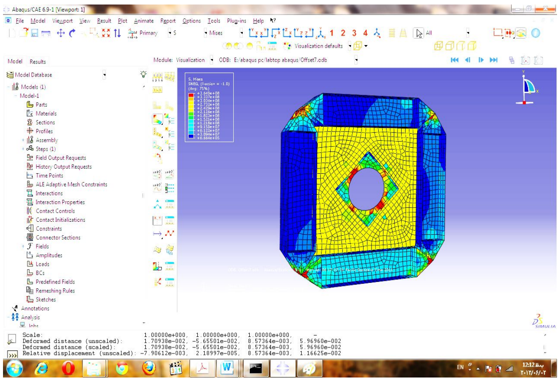

Figure 11: Shear wall with rhombus -shaped stiffener with a distance of 9 cm from the boundary elements

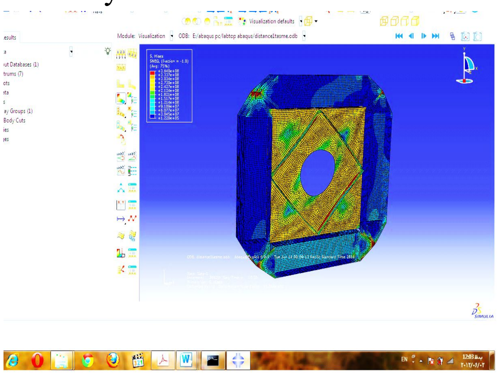

Figure 12: Shear wall with rhombus -shaped stiffener with a distance of 1 cm from the boundary elements

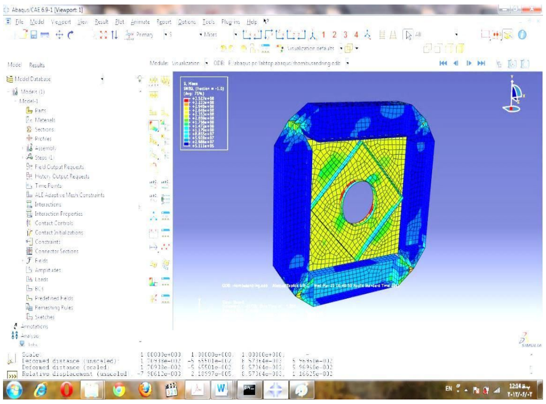

Figure 13: Shear wall with rhombus -shaped and annular stiffener

Carefully looking at the obtained diagram of different samples analysis in figure 14, it can be seen that the resistance is almost the same with each other in the samples with annular stiffener, annular stiffener and perpendicular to each other and annular and crisscross. It was also observed that the most closely matches can be seen with the sample without opening and in rhombus -shaped stiffener having 4 cm distance from the boundary elements.

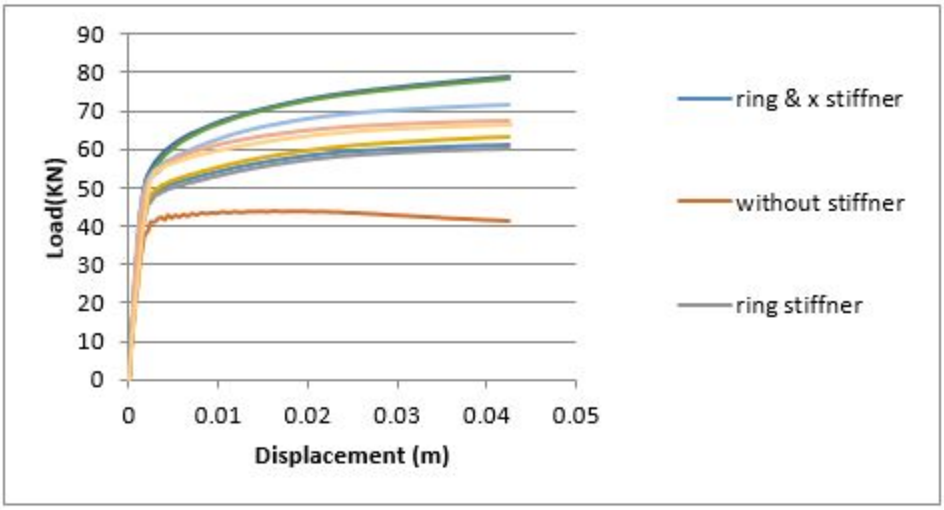


Figure 14: The obtained diagram of pushover analysis of samples with different stiffeners

## CONCLUSION

According to the output data analysis, the summary of the results was observed as follows:

- Placing the opening in the center of the panel leads to the decrease of the elasticity stiffness and lateral load capacity.

- By placing the opening in the center of the panel, the necessary lateral displacement rate for the sample failure is increased but the ductility is lower compared to the non-opening form.
- Stiffener existence increases the initial stiffness of the steel shear wall.
- The initial stiffness of the samples with a rhombus -shaped opening is very close to the sample of shear walls without opening.
-In the samples with rhombus -shaped stiffener the shear wall behavior was similar to shear wall without opening until rupture.

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