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Investigating the Effect of Openings on Steel Shear Walls Reinforced with Methods V and Λ and Reinforcement of the Openings' Edges

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ABSTRACT

Background and Aim: in recent decades, steel shear walls have been introduced as the first lateral load-resisting systems, implemented in several high-rise buildings. Due to their efficient performance, these systems are now widely used as systems resistant against lateral forces such as earthquakes and winds. This system includes a steel plate as high as the story and as wide as the span connected to the upper and lower beams as well as the lateral columns. In some cases, due to architectural reasons, or because of the building's utilities, the existence of an opening is inevitable. Methodology: in this research, the behavior of the shear walls consisting of several openings, and also the reinforcement of the openings using finite element method are modelled and analyzed by Abaqus software. Architectural needs and also ornamental purposes can be considered as the reasons for using openings in steel shear walls. Furthermore, nonstructural issues such as situation and direction of utility systems can be regarded as other justifications for using openings in steel shear walls. Results: in this research, first, the effect of openings is analyzed, and then, the openings' edges are reinforced and investigated. Based on the obtained results, the existence of an opening leads to a decline in the performance of steel shear walls. Conclusion: in this research, the openings' edges are reinforced. Based on the results, the reinforcements play a significant role in the performance of steel shear walls involving an opening.

Keywords: *Steel Shear Wall, Opening, Reinforcement, Abaqus.*

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1. INTRODUCTION

In the last three decades, using steel shear walls as lateral load-resisting systems in buildings has attracted the attention of researchers and designers. This new phenomenon that is rapidly spreading around the world has been employed for constructing new buildings or reinforcing the available ones, especially in earthquake-prone countries such as the US or Japan. The results of an economic comparison show that using steel shear wall system compared to a buckling steel frame, leads to 50% saving in steel consumption (Hosseini Lavasani, 2014).

Most of the researchers believe that there are many similarities regarding the behavior of a steel shear wall and a vertical plate beam in a way that the columns act as the webs of the vertical plate beam, while the steel plate acts as its body. Furthermore, floor beams act as transverse stiffeners of a plate beam (Astaneh-asl, 2001).

Steel shear wall is a simple system with no complexity in its implementation. Therefore, engineers, technicians, and technical workers can implement it by using the available technical knowledge and without the need for mastering new skills. The accuracy in the implementation is similar to the conventional precisions in implementing steel structures, the adherence to which leads to an increase in the high implementation confidence level compared to other systems. Moreover, considering the possibility of manufacturing the parts of this system in the factory and installing them in place, the implementation speed of this system is higher which in turn leads to the reduction of implementation costs (Hosseini Lavasani, 2014).

Compared to concrete shear walls, this system is a cleaner and faster in terms of implementation and more secure by considering the strength and behavior; moreover, it can be used not only in steel structures, but also in concrete structures.

Compared to braced systems and the shear strength, this system is stiffer than the braced systems (that are X-shaped); also, due to the possibility of making an opening in any desired point, it enjoys the function efficiency of all braced systems in this regard. The results of researches show that the system's behavior in a plastic environment; furthermore, its energy absorption rate is better than braced systems. Due to the variety of materials and connections in this system, stress balance is more efficient than other resistant systems such as buckling frames and different types of braced systems in which the materials are usually grouped and the connections are centralized. In addition, the system's behavior is particularly more appropriate in a plastic environment (Astaneh-asl, 2001).

Reinforced steel shear walls consist of a series of vertical and horizontal stiffeners. Assuming that this system is only affected by shear stress, two different buckling modes may form in the reinforced plate. If the stiffeners have sufficient moment of inertia, the buckling occurs locally under the plates between the stiffeners and is called local buckling mode. However, if the stiffeners are weak and are not sufficiently hard for transferring the buckling to the space under the plates, the buckling occurs all over the plate's surface, diagonally in the direction of the applied force. In this case, the stiffeners act as a part of the plate and buckle correspondingly, that is technically called the global buckling mode. Since the philosophy of using stiffeners is to transfer the buckling to the space under the plates and increase the buckling strength, therefore, the stiffeners' moment of inertia should be considered in a way that the local buckling under the plates occurs sooner than the global buckling of the plate. (Dr. Bahrami, 2011).

In 1993, Alqali et.al used finite element models and the models proposed based on the strip methods revised by Teimler and Kolak (1983), to repeat the results obtained by Kaseis et.al (1993) in laboratory. The result obtained from this research showed that a wall with thicker plates is not significantly stronger, since in either modes, column yielding is the controlling factor. Finite element models significantly predicted hardness and capacity more than laboratory results. These differences are caused by the difficulty in modelling the primary deficiency of the plates and also the inability to model outside-the-surface deformations of the frame's components. The sample was modelled by changing the connections, reducing the thickness of plates, decreasing the strips' angles, and corresponded well with the results of finite element model. An analytical model was also developed for predicting the hysteresis circular behavior of steel shear walls with thin plates. This model was based on the strip model but with crossed strips, necessary for obtaining the hysteresis behavior. Using an experimental hysteresis stress-strain relationship, from the abovementioned hysteresis model, a desirable correspondence with laboratory results was reported (Hosseini Lavasani, 2014; Moharami et al., 2009).

Kharazi et al. (2004) studied the design of steel shear walls in terms of separate shear and buckling deformations that occurred in a multistorey frame. They suggested a model of plate-frame deformed interaction for analyzing shear and buckling deformations and the resulting forces in steel shear walls. The purpose was to explain the interaction between those components and determine the share of deformations and strength.

Saboori and Gholhaki performed several finite element analyses on single-story shear panels involving stiffeners with various plate thickness. The analyses were divided into two categories, with and without openings. In the section dealing with the analysis of panels with openings, square shaped and circular openings were created in the center of the panels. The results of the analyses showed that the decrease in the strength and hardness of panels involving an opening compared to those without an opening, is a function of the ratio of the opening's area to panel's area and can be used in designing. The analyses also showed that although the strength and hardness of panels decrease by creating an opening, their ductility increases (Hosseini Lavasani, 2014).

In this research, first, a single-story model is modelled using Abaqus software, and then, after installing the stiffeners and creating openings with different shapes and in different places, the models are studied and analyzed. The hysteresis diagram related to each model is extracted from the software and then, these diagrams are compared with each other.

2. METHODOLOGY

In this research, Abaqus software is used for modelling and Dr. Saboori Qomi's single-story model (2008) is used for validation. Modelling of the laboratory sample in Abaqus software is done in the 3D mode and elements such as Shell-Extrusion-Deductile are used. The characteristics related to all of its cross-sections correspond with the laboratory sample.

The sample's scale is 1/3, and its height and width are 1250 and 1590 millimeters, respectively. In the laboratory sample of the steel shear wall, the plate's thickness is 2 millimeters. For connecting the plate to the frame, a 60*60*60 millimeters angle bar is used. For accurate welding of the plate and the angle bar's edge, one side of the angle bar is lathed so that its edge is totally flat. Therefore, one side of the angle bar is reduced by 50 millimeters. In constructing the laboratory sample, first, the plate, the angle bar, and the stiffeners are connected together, and then, the beam and the column are installed around them. Usually in welding, the heat produced in the plate leads to a twist in the angle bar by the plate. Taking this issue into account, a 60*60*60 millimeters angle bar is used due to its sufficient resistance against twisting (Saboori Ghomi. Asad Sajadi, 2013).

The load is applied by two hydraulic jacks situated on both sides of the sample. An ergometer is situated behind each jack for measuring the amount of force. Triple-axis strain gauges are installed in the middle of the plate and near the horizontal and perpendicular edge of the plate. For determining the threshold of formation of plastic hinge on the top and at the bottom of the column in steel shear wall sample, single-axis plastic strain gauges are used. Furthermore, the theory of soft steel (energy absorbing steel) is used for designing, and thus the aforementioned walls are classified as ductile steel shear walls.

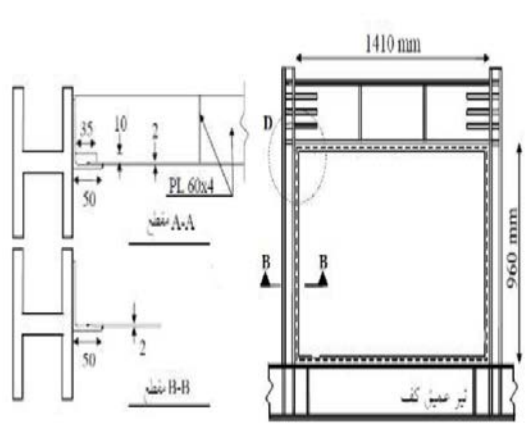

Figure 1. Cross section of the examined steel shear wall model (Saboori Ghomi. Asad Sajadi, 2013)

Table 1. Mechanical properties of laboratory sample's members

Members	Flow stress (N/mm²)	Ultimate stress (N/mm²)
Plate	192.4	288.7
column	414.8	551.7

The sample has been subjected to periodic load according to ATC-24 standard. The sample's limit load of 789.6 kilonewton was obtained in 39 millimeters of displacement. The ratio of the maximum lateral displacement of the sample to the column's height is 5.34%. The number of periodic loading is 32 rings.

The general model used in this research is a single-story model in which the steel shear wall is plain, without any openings or reinforcements. The model's scale is 1/3, and its height and width are 1250 and 1590 millimeters, respectively. The dimensions of the beam's cross-section are 140*290 millimeters. The thickness of the web and body of the beam is considered as 20 millimeters. The dimensions of the column's section are 140*290 millimeters. The thicknesses of the web and body of the column are considered as 20 and 15 millimeters, respectively. The dimensions of the plate are 1410*960 millimeters. For all of the sections, a Poisson's ratio of 0.3 and a 210000 Pas Young's modulus is used.

The characteristics of the main model, called S-1, are shown in the following table:

Table 2. Characteristics of S-1 model

Model	Column's dimensions (mm)	Beam's dimensions (mm)	Plate's dimensions (mm)	Opening's dimensions (mm)	Place of the opening	Opening type
0	1410*960	290*140	90*140	S-1	-	-

Table 3. Characteristics of all models

	Reinforcement method	Opening type	Opening place	Reinforcing the opening's edge	Opening dimensions (mm)
s-1	None	none	none	none	0
s-2	Λ	none	none	none	0
s-3	Λ	door	Middle	none	330*700
s-4	Λ	door	Middle	yes	700*330
s-5	Λ	Window	Middle	none	400*400
s-6	Λ	Window	Middle	yes	400*400
s-7	Λ	Window	Side-top	none	350*350
s-8	Λ	Window	Side-top	yes	350*350
s-9	Λ	Utility	Side-top	none	150*150
s-10	Λ	Utility	Side-top	yes	150*150
s-11	Λ	Utility	Middle-bottom	no	150*150
s-12	Λ	Utility	Middle-bottom	yes	150*150
s-13	Λ	Utility	Side-middle	no	150*150
s-14	Λ	Utility	Side-middle	yes	150*150
s-15	V	none	none	no	0
s-16	V	Window	middle	no	400*400
s-17	V	Window	middle	yes	400*400
s-18	V	Utility	Top-middle	no	150*150
s-19	V	Utility	Top-middle	yes	150*150
s-20	V	Utility	Side-middle	no	150*150
s-21	V	Utility	Side-middle	yes	150*150

3. RESULTS

1. Models Reinforced by Using Method Λ

The first model involves a stiffener, lacks an opening and is called S-2. In this stage, four stiffeners are installed on both sides of the plate in the steel shear wall, and are connected to the plate as shown in figure 8.

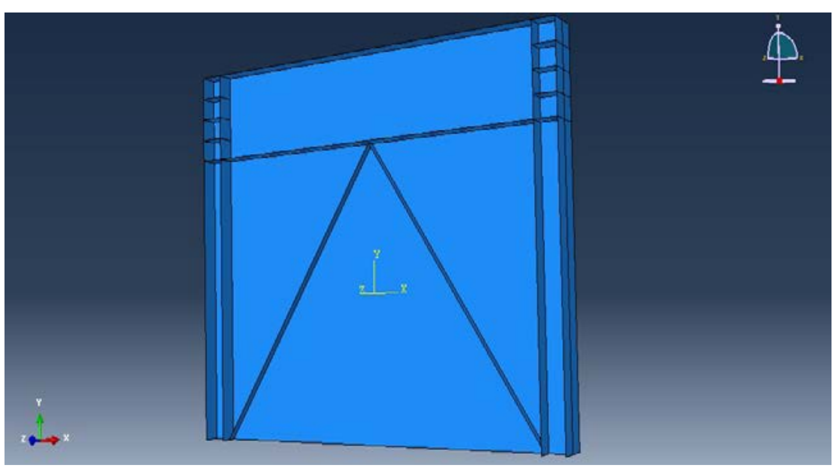

Figure 2. Model of the steel shear wall stiffened through method Λ (S-2)

The stiffeners have a width of 60 millimeters and a thickness of 4 millimeters. All of the connections and loads are considered based on plain steel shear wall (S-1).

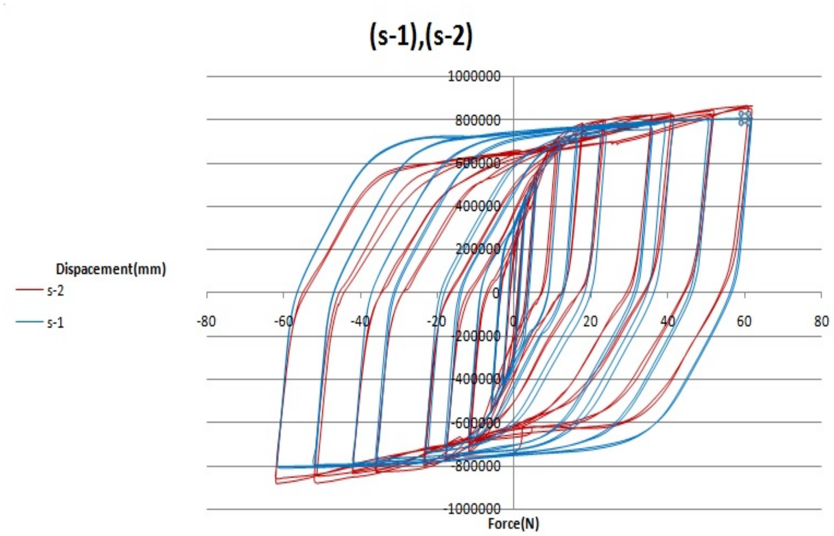

Figure 3. Comparative hysteresis diagram of (S-1) and (S-2) models

The steel shear wall that is reinforced by using method **Λ** and involves an opening and a "door" (S-3) is compared to (S-2) model.

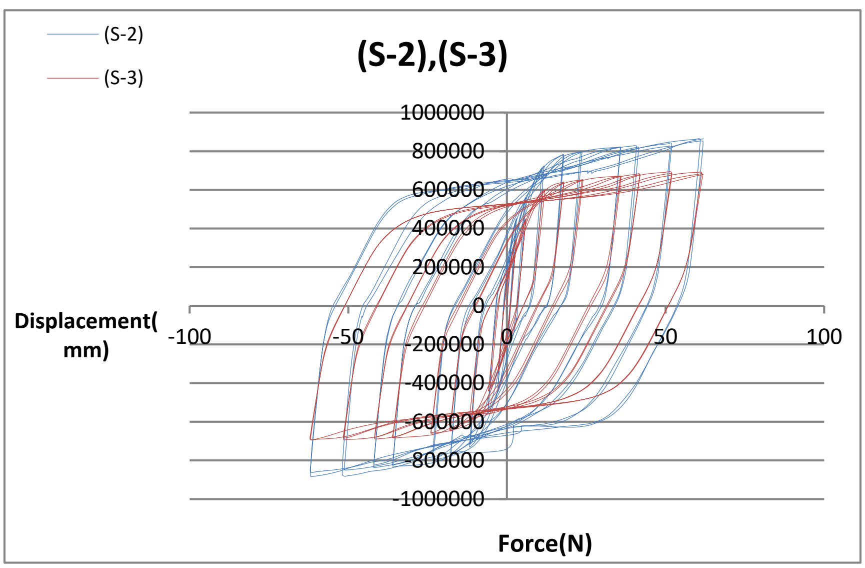

Figure 4. Comparing the hysteresis diagrams of models (S-3) and (S-2)

The steel shear wall that is reinforced using method **Λ** and involves an opening, a "door", and reinforced opening edges (S-4) and (S-3) model with reinforced opening edges are analyzed.

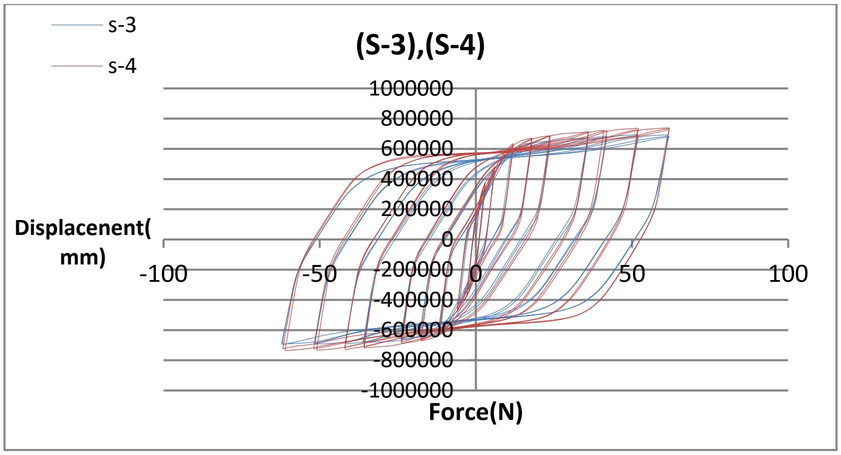

Figure 5. Comparing the hysteresis diagrams of models (S-3) and (S-4)

Model of the steel shear wall that is reinforced by using method **Λ** and involves a window opening in the middle (S-5) and (S-6) model of the steel shear wall that is reinforced using method **Λ** and involves a window opening in the middle and modified by reinforcing the opening's edges are analyzed.

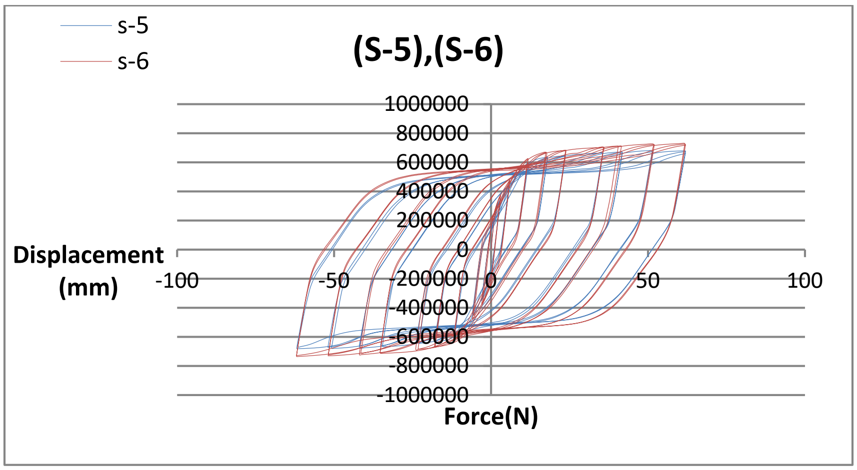

Figure 6. Comparing the hysteresis diagrams of models (S-6) and (S-5)

Model of the steel shear wall that is reinforced by using method **Λ** and involves a window opening on the side (S-7) and model of the steel shear wall that is reinforced by using method **Λ** and involves a window opening on the side, with reinforced opening edges (S-8) are compared.

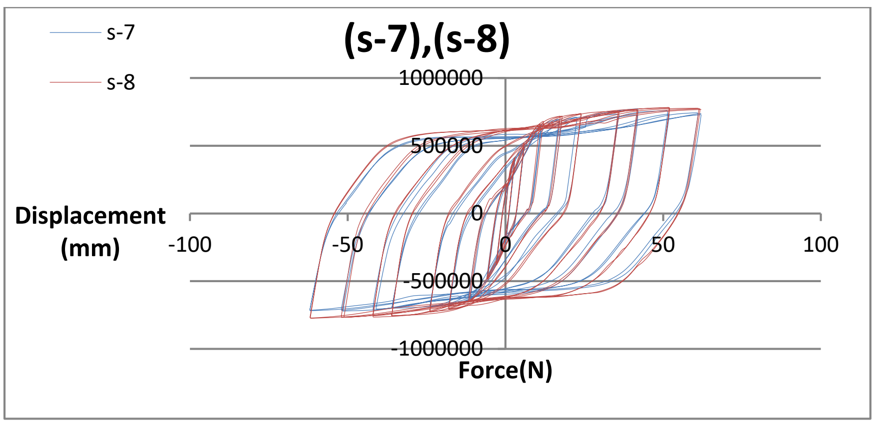

Figure 7. Comparative hysteresis diagrams of models (S-7) and (S-8)

The model of the steel shear wall that is reinforced by using method **Λ** and involves a utility opening on the top side (S-9) and model of the steel shear wall that is reinforced using method **Λ** and involves a utility opening on the top side with reinforced opening edges (S-10) are compared.

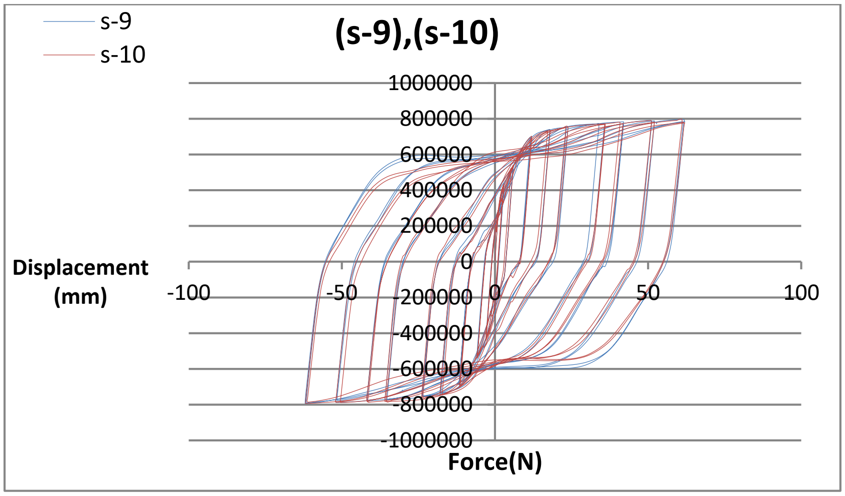

Figure 8. Comparative hysteresis diagrams of models (S-9) and (S-10)

The model of the steel shear wall reinforced by using method **Λ**, involving a utility opening at the bottom and middle of the wall (S-11) and model of the steel shear wall reinforced by using method **Λ** and involving a utility opening at the bottom and middle of the plate, with reinforced opening edges (S-12) are compared. In the following, hysteresis diagrams of models (S-11) and (S-12) are compared.

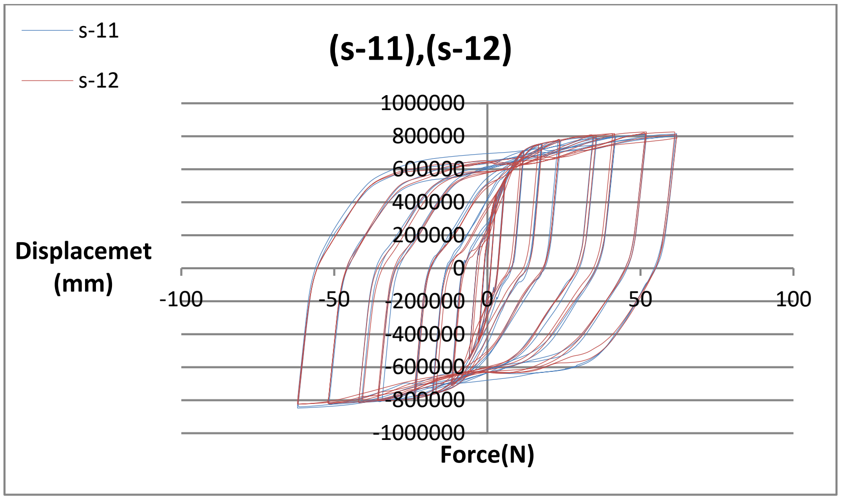

Figure 9. Comparative hysteresis diagrams of models (S-11) and (S-12)

The model of the steel shear wall that is reinforced by using method **Λ** and involves a utility opening in the middle and on the side of the plate (S-13) and model of the steel shear wall that is reinforced by using method **Λ** and involves a utility opening in the middle and on the side of the plate, with reinforced opening edges (S-14) are compared. In this model, stiffeners with a dimension of 60 millimeters and thickness of 4 millimeters are used.

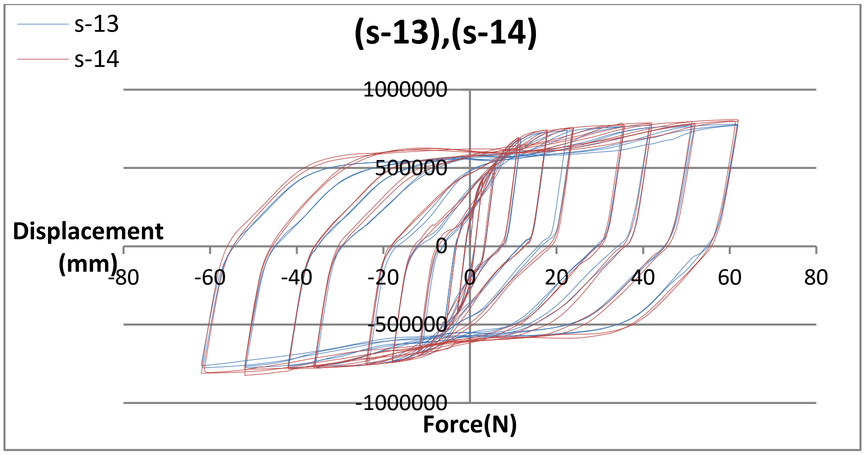

Figure 10. Comparative hysteresis diagrams of models (S-13) and (S-14)

2. Models Reinforced Using Method V

The model of the steel shear wall reinforced by using method **V** with connection and loads correspondent with plain steel shear wall (S-1) are compared to one another. In the following, hysteresis diagrams of models (S-15) and (S-1) are compared.

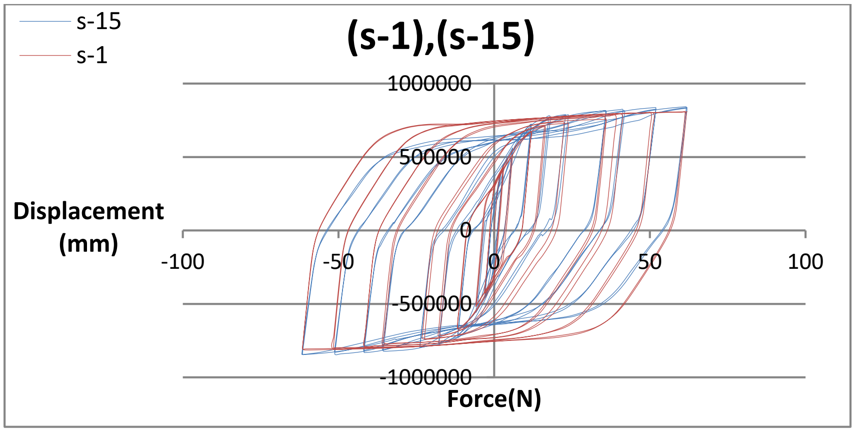

Figure 11. Comparative hysteresis diagram of models (S-15) and (S-1)

The model of the steel shear wall reinforced by using method **V**, involving a window opening in the middle (S-16) with the model of the steel shear wall reinforced by using method **V**, involving a window opening in the middle, with reinforced opening edges (S-17) are compared.

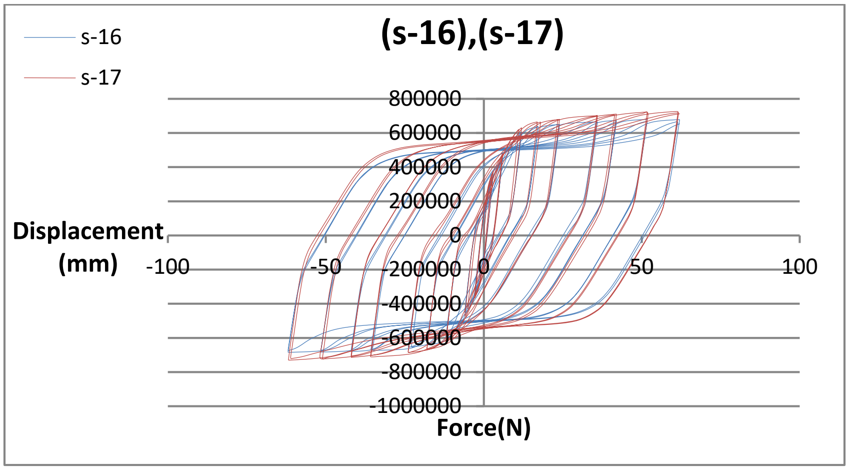

Figure 12. Comparative hysteresis diagram of models (S-16) and (S-17)

The model of the steel shear wall reinforced by using method **V**, involving a utility opening in the middle and on top of the plate (S-18) with the model of the steel shear wall reinforced by using method **V**, and involving a utility opening in the middle and on top of the plate, with reinforced opening edges (S-19) are compared.

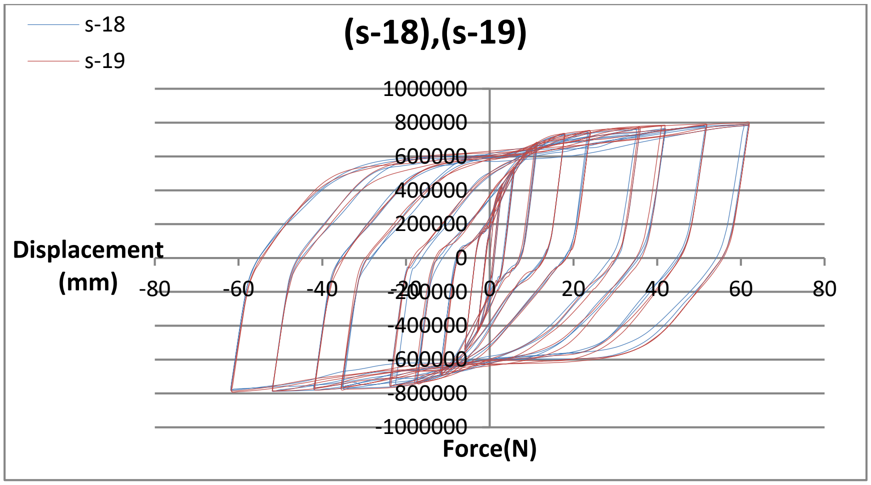

Figure 13. Comparative hysteresis diagram of models (S-18) and (S-19)

The model of the steel shear wall reinforced by using method **V**, involving a utility opening in the middle and on the side of the plate (S-20) with the model of the steel shear wall reinforced by using method **V**, involving a utility opening in the middle and on the side of the plate, with reinforced opening edges (S-21) are compared.

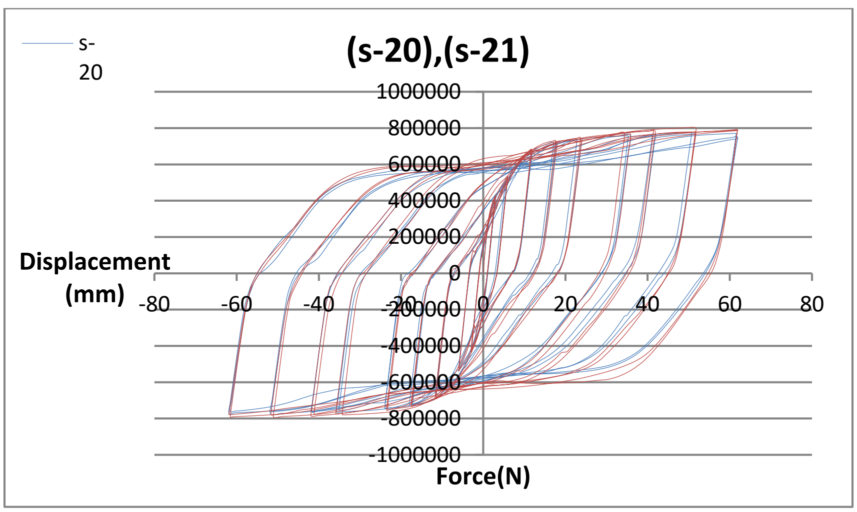

Figure 14. Comparative hysteresis diagram of models (S-20) and (S-21)

4. CONCLUSION

Based on the diagrams obtained from the models in Abaqus software, it is evident that reinforcing the steel shear wall by using both methods (**V** and **Λ**) leads to an increase in bearing capacity of the steel shear wall. Furthermore, comparing the hysteresis diagrams of the models with one another, the following conclusions can be made:

Comparing the hysteresis diagrams of (S-1) model that is a plain steel shear wall, with (S-2) model that is a steel shear wall reinforced using method **Λ**, it can be understood that the reinforced wall's bearing capacity is 11.84 percent higher than the plain shear wall.

Comparing (S-2) and (S-3) models that are reinforced steel shear wall, and reinforced steel shear wall involving a door opening respectively, it can be understood that the creation of an opening in the steel shear wall leads to a 25 percent decrease in bearing capacity, compared with the model without an opening.

In (S-3) and (S-4) models, the characteristics of which are shown in table 3, the bearing capacity of the model with reinforced opening edges is 9 percent higher than the other model.

In (S-5) and (S-6) models, the bearing capacity of the model with reinforced opening edges is 9 percent higher than the other model.

In (S-7) and (S-8) models, the bearing capacity of the model with reinforced opening edges is 6.9 percent higher than the other model.

Comparing the hysteresis diagrams of (S-9) and (S-10) models, and with regards to the position of the openings, the two diagrams were approximately correspondent with one another, and did not lead to significant changes in bearing capacity.

Comparing the hysteresis diagrams of (S-11) and (S-12) models, and with regards to the position of the openings, the two diagrams were approximately correspondent with one another, and did not lead to significant changes in bearing capacity.

In (S-13) and (S-14) models, the bearing capacity of the model with reinforced opening edges is 12.7 percent higher than the other model.

In (S-16) and (S-17) models, the bearing capacity of the model with reinforced opening edges is 10.2 percent higher than the other model.

Comparing the hysteresis diagrams of (S-18) and (S-19) models, and with regards to the position of the openings, the two diagrams were approximately correspondent with one another, and did not lead to significant changes in bearing capacity.

In (S-20) and (S-21) models, the bearing capacity of the model with reinforced opening edges is 8.7 percent higher than the other model.

Based on the models obtained by the software, it is evident that in both methods the reinforcement s cause the occurrence of buckling mode that in turn shows the desirable behavior of methods **V** and **Λ**.

Comparing the hysteresis diagrams of the models reinforced using methods **V** and **Λ**, it can be realized that the steel shear wall reinforced using method **Λ** is more efficient than the steel shear wall reinforced using method **V**.

In the walls reinforced through both methods, creation of an opening resulted in a decrease in the walls' bearing capacity which is relative to the type and size of the opening. As it can be seen in the diagrams, a window opening leads to a decrease in the bearing capacity of walls in both methods. Furthermore, it is worth mentioning that the decrease in bearing capacity is larger when the opening's dimensions are bigger.

Due to the architectural limitations in buildings, and also the fact that these constraints that include utility, window, or door openings are inevitable, it is possible to increase the bearing capacity of the walls by reinforcing the opening edges. The aforementioned issue is evident in the hysteresis diagrams of the models. In comparative hysteresis diagrams, it can be clearly seen that reinforcing the openings' edges has a significant effect on the bearing capacity of steel shear walls.

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