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Evaluation and Comparison of Seismic behavior of Steel Plate Shear Wall Containing Circular and Rectangular Openings under Cyclic Load

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ABSTRACT

Considering this point that Iran is located in the seismic belt, buildings must have enough strength against seismic loads. One of the methods against seismic load is the utilization of steel plate shear walls. Steel plate shear wall has been taken into account considerably in recent four decades in such a way that in many countries including the USA, and Japan using this system has become usual and common for strengthening of buildings against earthquake. Performed studies show a good performance of this system against lateral loads. Evaluation of seismic behavior of shear walls in various conditions can be a good guideline for optimum design of these walls. In this research, three different models of the shear wall have been built in finite element software of ABAQUS, and seismic properties of them including displacement and corresponding force or yielding limit, displacement and corresponding force or ultimate limit, absorbed energy and initial stiffness have been evaluated. Important results were obtained from performed research such as the existence of opening in steel plate shear wall in any state creates weak seismic performance in the wall, however, it can be profitable economically. Creating of opening in the middle plate of the shear wall in an amount of 17% can decrease the absorbed energy level of an earthquake by up to 15%. The seismic properties of shear walls containing rectangular and circular openings do not differ greatly from each other, therefore it is suggested that rectangular openings be used so that in addition to easier construction, the surrounding of the opening can be strengthened with FRP plates in case it was needed.

Keywords:

Steel plate shear wall, Opening, Seismic load, Finite element analysis, ABAQUS

1. Introduction

There is the various lateral force resisting systems to resist the lateral loads of wind, earthquake, and explosion. Designers can use any of them considering the existing conditions and limitations in the shape of the building. Using the steel plate shear wall is a superior way relative to other lateral force resisting systems, because of its strength, ductility, high energy absorption, appropriate adjustment of stresses in a plastic environment, very high strength relative to the bracing with a uniform span, no limitation relative to the creation of opening, occupation of smaller space relative to the concrete shear wall, higher building speed in the place, and ….The steel plate shear wall is used in both forms of strengthened, non-strengthened. The steel plate can be strengthened by stiffeners especially in the elastic region to prevent buckling of the steel plate. By considering the high strength of the steel plate and benefiting from the post-buckling behavior of it, the steel plate is thin even in the tall steel plate shear walls and against large shear forces. Therefore, stiffeners can be used to prevent buckling of steel shear plate wall under service load instead of increasing the plate thickness which is non-economical totally. On other hand, utilization of solid filled plate for steel plate shear wall is not logical, because the stress distribution throughout the plate is not uniform due to the lateral loading. Therefore, some holes can be created in the wall's plate in the sections where the stress in the wall is low. In this paper, the non-linear behavior of the shear wall containing the opening, and the effect of circular and rectangular openings in the steel plate shear walls are evaluated. Since the early 1970s, investigations on the steel plate shear wall have been started. The main goal of these analytical investigations is the analysis and design of steel plate shear walls to be feasible in a simple state and without the need for the definition of many complexities. At first, this job has been done with various modeling of thin steel plate shear walls without stiffeners to understand the real behavior of this system before and after buckling. Minora and Akiama used the classic theory of plates after buckling to predict the buckling capacity of filler plate, diagonal tension field behavior, and cyclic and uniform behavior of the steel plate shear wall without stiffeners [1]. Then the investigation of the multi-strip modeling method comes in which this method is discussed based on the suggested diagonal tension field by Wagner in 1931. Tourian et al. in addition to the multi-strip model presented a simple analytical model using modeling of tensional field behavior by a series of oblique double head jointed tensional members [2]. Tourian and et al. presented the pratt truss model which is recognized as the equivalent restraint model or equivalent stratified model for analysis of thin steel plate shear wall [2]. The performed research at the University of British Columbia by Rezaie has shown that the multi-strip model is an inappropriate method and presents inaccurate results for a wide range of steel plate shear walls. Laboratory studies showed that the tension angle in the corners is closer to the vertical angle and in the middle of the plate, this angle is closer to the horizon trend. Its reason is the interaction effect of filler plate and boundary elements in the corners [3]. Elgalie et al. utilized a transverse stripped model using hysteretic stress-strain relation to predict hysteretic behavior of steel plate shear walls. In this method, transverse truss members were used for modeling tensional field behavior in different directions and during the returning of cyclic loads [4]. Sabourighomi et al. presented a method for total general modeling of steel plate shear wall systems. In this method, the behavior of the steel plate shear wall and frame is considered separately and the interaction effect of these two elements is evaluated [5]. Driver et al. showed that multi-stripped modeling approximates elastic stiffness and the total capacity of steel plate shear wall lower than real value. Its reason was the non-consideration of the compressive diagonal effect before buckling in the calculation of strength and stiffness of the filler sheet [6]. Behbahanifard and Gourendin was performed a finite element modeling based on explicit non-linear dynamic formulation using ABAQUS software. They used a cinematic stiffening model for simulation of the bauschinger effect [7].The first comprehensive laboratory research work in the modeling of the behavior of steel plate shear walls was performed by Tkahashi et al. (1973). The experiment was performed on 12 samples of one-story and two samples of two-stories with and without opening [8].Timler and Coolak for evaluation of the accuracy of the presented method by Torben et al. (stripped) tested two samples in which beams were positioned vertical and columns were positioned horizontally. The researchers concluded that the torsional stiffness of columns impacts the angle (suggested relation of Tourbern et al.). In 1987 Troumpush and Coolak tested similar samples of Timler and Coolak with joint (hinge) connection of beam to column and prestressed columns under axial load, which going under cyclic loading. Using this test, they showed that the shear wall has very good strength and high ductility [9]. In the United States, Elgali and Kaksiz performed some studies on the steel plate shear wall in 1993. The samples were 6 frames of three stories, a span, and without stiffeners, and were gone under cyclic loading in the roof level [9]. Nakashima et al. were performed some tests on the steel plate shear wall with low yielding stress under cyclic load [10]. In the years 2000 to 2001, wide research was performed by Dr. Astanehasl and Gao on the steel plate shear wall for the determination of stiffness and ductility under cyclic loading. In the first sample, the ratio of height to width was equal to 1.5 and in the second sample, this ratio was equal to 1. The first sample showed good behavior and very high ductility [11]. Researchers at Buffalo University in 2004 were tested a sample of one story to evaluate the ductility of steel plate shear wall. The steel material was a steel plate with low yielding stress and the ratio of width to height of the wall was 2. The sample has shown a displacement of 6.4 times of yielding displacement in each side of the strength. Therefore the ductility ratio of that was according to ATC-24 protocol and Popov theory equal to 6.4 and 12.8 in order [12]. A sample of steel plate shear wall was tested by Berman and Bernova. The section of employed columns in this test was W310x143 and the section of employed beams was W460x128. The sample was gone under cyclic loading according to ATC-24 Protocol. The sample shows the relative displacement of 3.7 percent of the shown strength and a ductility ratio of 12 percent [13]. two shear walls were designed and tested with the scale of 1/3 of real size under cyclic loading by Behbahanifard and et al [14]. Farzampour et al. [15] implemented the corrugated infill plates to eliminate the effects of opening presence in SPSWs. The investigations showed that utilizing the corrugation angle of 30°, despite decreasing the ultimate strength, improved the ductility and initial stiffness. Ding et al. [16] showed that CSPSWs with opening which has supported by stiffeners had improved the ultimate strength and energy dissipation; however, the effects of opening inside of the infill plate, and the stiffness of the boundary elements are not considered in these studies. Along the same lines, to reduce the effects of openings on steel plate shear walls, Tabrizi and Rahai [17] introduced a method in which the infill plate corners were reinforced with FRP laminates. The results indicated that the stress concentration on the corners of openings are limited. It is also observed that the ultimate strength and initial stiffness are increased by 66% and51%, respectively. Along the same lines, by examining eight experimental specimens with two different plate thicknesses and four circular openings at the center under the cyclic loading, Valizadeh et al. [18] concluded that the existence of opening reduces the initial stiffness and ultimate strength of the system significantly; although various locations. Formisano et al. [19] addressed the behavior of aluminum plate shear walls (APSWs) as an innovative system capable of providing a significant capacity for existing structures to resist against seismic and wind loads. The results demonstrated that these devices can improve structuralbehavior and providesuperior strength improvementand energy absorption. However, when these plates are used in a completely solid form in a structure, excessive stress may develop around the in- stallation location. To avoid this issue, perforations were created in the plate panels. In this research, 13 perforation patterns with different opening ratios were considered in aluminum plates. The findings showed that perforated plates are a proper alternative for solid panels for strengthening new and existing structures. Moreover, Moghimi and Driver [20] addressed the effect of regular opening patterns on the demands of SPSW columns and found that although the openings significantly reduced the shear capacity of the infill plate, they might not decrease the force demands on the columns. Valizadeh et al. [21] and Formisano et al. [22] experimentally studied the cyclic behavior of SPSWs with a centrally-located circular opening and assessed the effect of this central opening and its dimension on a number structural properties, including initial stiffness, strength, and energy absorption.

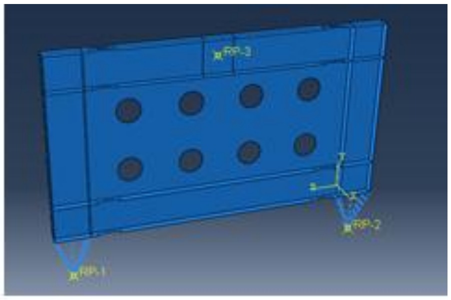
2. The Research Methodology

In this research, ABAQUS finite element software was used and in addition to modeling the steel plate shear wall in the complete form, two shear wall models with different openings were modeled. One of the models had an opening in circular form and the other one with rectangular form. The seismic properties that were extracted from these three models and were compared included: seismic properties such as displacement and its corresponding force or yielding limit, displacement and its corresponding force or ultimate limit, absorbed energy, and initial stiffness. The built models are according to Table 1.

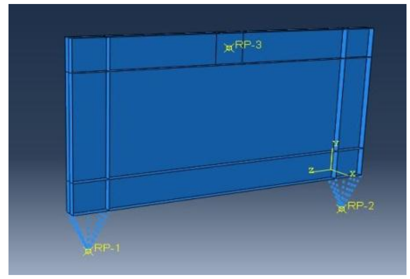
Table 1.Properties of built models.

Model number	Model Type	Opening Percentage
1	Steel plate shear wall without opening	0
2	Steel plate shear wall with a meshy circular opening	17
3	Steel plate shear wall with a middle rectangular opening	17

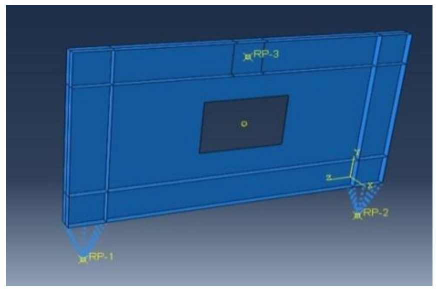
It should be pointed out that the employed beam in these models is W18 X 65 type and the employed column is W18 X 71 type. The width of the shear wall panel is 4 meters and its height is 2 meters. The thickness of the shear wall panel is equal to 4 meters and its height is equal to 2 meters. The thickness of the middle plate is equal to 2.6 millimeters. Model 2 has 8 circular openings with a radius of 18 centimeters and model 3 has an opening of 1.15 meters by 0.77 meters. Therefore around 17% of the middle plate has an opening. In the most of performed research, the surface of the opening relative to the total surface of the shear wall is considered equal to 15 to 20 percent. Figure 1 shows the view of the geometry of the models.



Model number 2



Model number 1



Model number 3

Figure 1. The geometry of built models.

2.1. Modeling Procedure

For modeling, it was assumed that the shear wall is in the form of rigid connections (Connection of the middle plate to the beam and column) and also joint (hinge) connection in the base exists in which only the possibility of rotation around an axis exists. Therefore, with insertion of load and with considering the intensity of load, the shear wall panel rotates to left and right in a cyclic form. Hence, we can evaluate the behavior and deformations of the wall. Also, for modeling the wall, a shell element has been used. The beams, columns, base abutment, the stiffeners of the columns, and the middle plate are designed separately and their constructing materials and the properties of the section were assigned to them. Finally, in assembly effort, they were put on each other until the shape of the shear wall is completed. Since the ABAQUS software does not have a unit, for using this software, a unit system was assumed and the job progressed based on that. In this project kilogram unit (Kg) and centimeter unit (Cm) was used. Also, for making the results closer to reality, an initial imperfection should be applied to the structure. In other words, the effect of non-homogeneity and some construction errors and which exist in reality should be modeled, so that the structure gets evaluated under influence of these imperfections more real results get obtained. For this matter in the first mode of the shear, wall buckling was extracted, and then equal to 1-millimeter deformability of the first mode of buckling was applied to the structure. In figure 2, a view of the first mode of buckling can be seen which has been extracted for the first model.

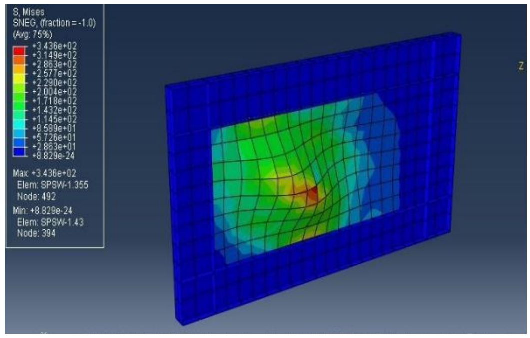


Figure 2. The first mode of buckling for considering the initial imperfection.

2.2. Material Properties

One of the most important problems in this research was considering the technical properties and characteristics of available materials in the modeling. The properties of used materials can be seen in Tables 2. It should be mentioned that in two columns at the right of the table the yielding stress and plastic strain are located in front of each other, correspondingly.

Table 2. Technical properties of materials used in the modeling

Row	Material	Density (Kg/cm3)	Elasticity modules (Kg/cm2)	Poison Ratio	Yielding stress (Kg/cm2)	Plastic strain
1	A36 Steel	0.007849	2100000	0.3	1651	**0**
					3050	**0.2**
2	A572 Steel	0.007849	2100000	0.3	3451	**-**
					4800	**0.17**

It should be mentioned that the A36 steel (LYS[5] steel) was assigned to the middle plate and A572 steel which is common construction steel was assigned to the beam and column sections. In figure 3, the stress-strain graph which has been extracted from stress-strain graphs has been shown for these three types of steel. It should be mentioned that the A537 and A514 steels which exist in the graph were not used in this modeling.

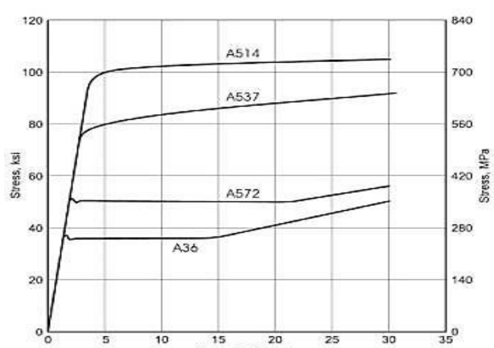


Figure 3. The stress-strain graph of steels used in the modeling.

2.3. Loading

For accurate evaluation of deformation procedure and extraction of seismic parameters of the shear wall, correct and precise loading is very important. For this matter, using the loading protocol of ATC-24, a loading was applied on the shear wall in all models according to figure 4. The time for loading is 96 seconds in which displacement is applied to the middle section of the upper beam and causes rotation in the shear wall panel around the first axis e.g. x.

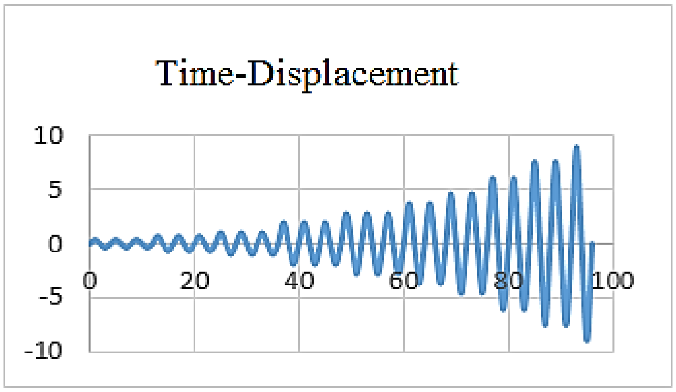


Figure 4. Loading graph (Displacement based on time).

2.4. Analysis and Results

Considering that there are various analysis methods in the ABAQUS software, choosing the appropriate analysis method depending on the required results is very important. The implicit analysis methods have weak performance considering the behavior and geometrical complexity of steel plate during the buckling of out of plate and development of the tensional field, and these methods cause the divergence of the results, therefore the explicit analysis method was used. However, the dynamic explicit method is used based on this condition that the amount of kinetic energy relative to the amount of internal energy is a low value, which confirms this matter that our assumption of dynamic analysis, the speed, and time of analysis is correct. In all of the analyzed models, this condition is valid, therefore the selection of dynamic explicit analysis is appropriate.

3. Calibration

The base papers which were used in this research are the following two papers of Vian, & Purba [23].The geometrical properties of the model of the test of Berman and Bernova can be seen in Figures 5. For calibrating the obtained results from modeling, the results of the Berman and Bernova models were considered.

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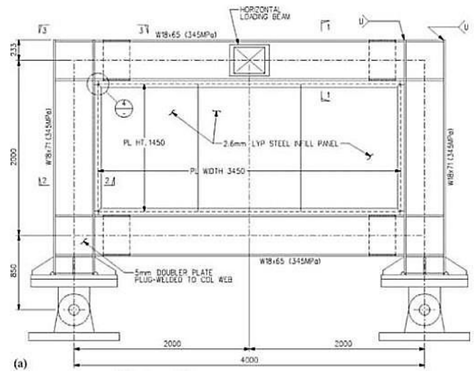

Figure 5. The geometrical properties of Berman and Bernova model.

In the base paper, three models have been built, from which the required model for calibration is the third model (S2), the shear wall without opening, and with the middle plate of LYS. Also, for easing the comparison, the proposed units in the paper were converted to SI units so that the difference with calibration modeling be determined. Considering that the properties of ultimate strength and initial stiffness have been evaluated in the paper, these two properties were used to determine the percentage of difference. The comparison of obtained results has been shown in table 3-1 and the graphs of figure 6 and 7 show a good correlation between the results of modeling and base paper.

Table 3. Comparison of the results of base paper and results of the calibration model.

Initial Stiffness Kg/Cm	Ultimate strength Kg	Yielding strength Kg	Yielding limit displacement Cm	Model
136429	205600	76400	0.56	**Calibration**
138171	215670	-	-	**Paper**
1.26	4.66	**Difference (percentage)**		

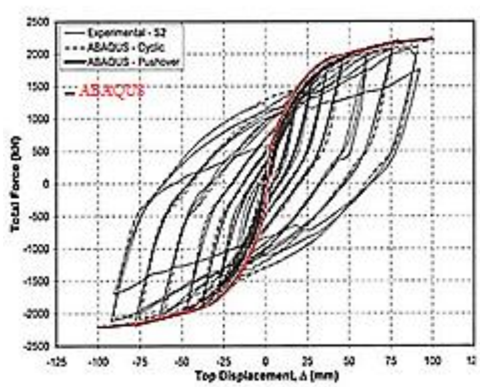

Figure 6. Comparison of hysteresis graphs of base paper and modeling.

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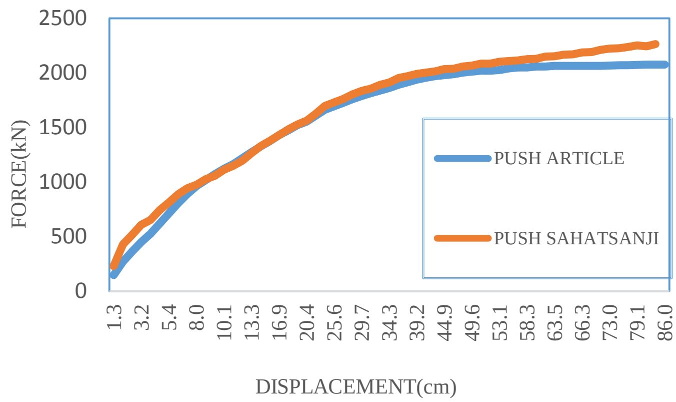
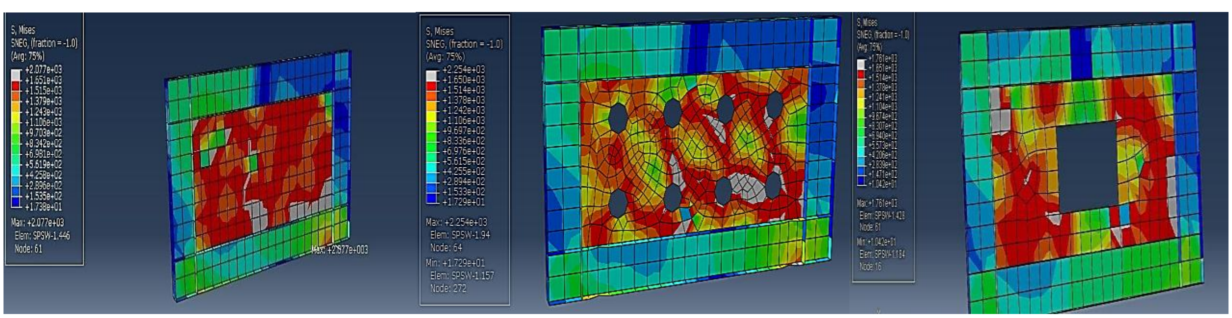


Figure 7. Comparison of push-over graphs of base paper and modeling.

4. Results Evaluation

4.1. Evaluation of Yielding and Ultimate Limits

The yielding and ultimate limits should be determined for the evaluation of the performance of the shear wall**.** The yielding limit for a shear wall is the creation of a diagonal tensile field in the middle section and is yielding of that section. The ultimate limit according to performed researches such as Berman and Benova research is the creation of failure or rupture in the beams connected to the middle plate. In figures 8 and 9, the yielding limit and ultimate limit can be seen for three models. As can be seen, the yielding in the first model (without opening) has happened in the edges of the middle plate, and in the second and third models, it has happened around the openings and the corners of the middle plate. Also, the ultimate limit in all three models of failure is in the lower beam connected to the middle plate.



(A) (B) (C)

Figure 8. The yielding limit of proposed models (A) First model (B)Second model(C)Third model.

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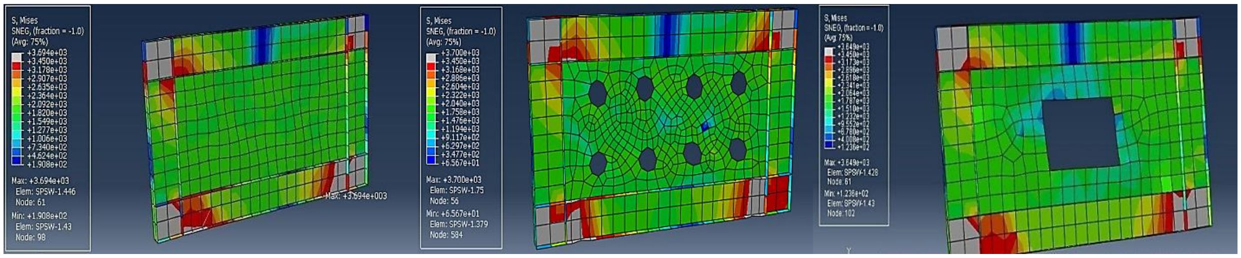


(A) (B) (C)

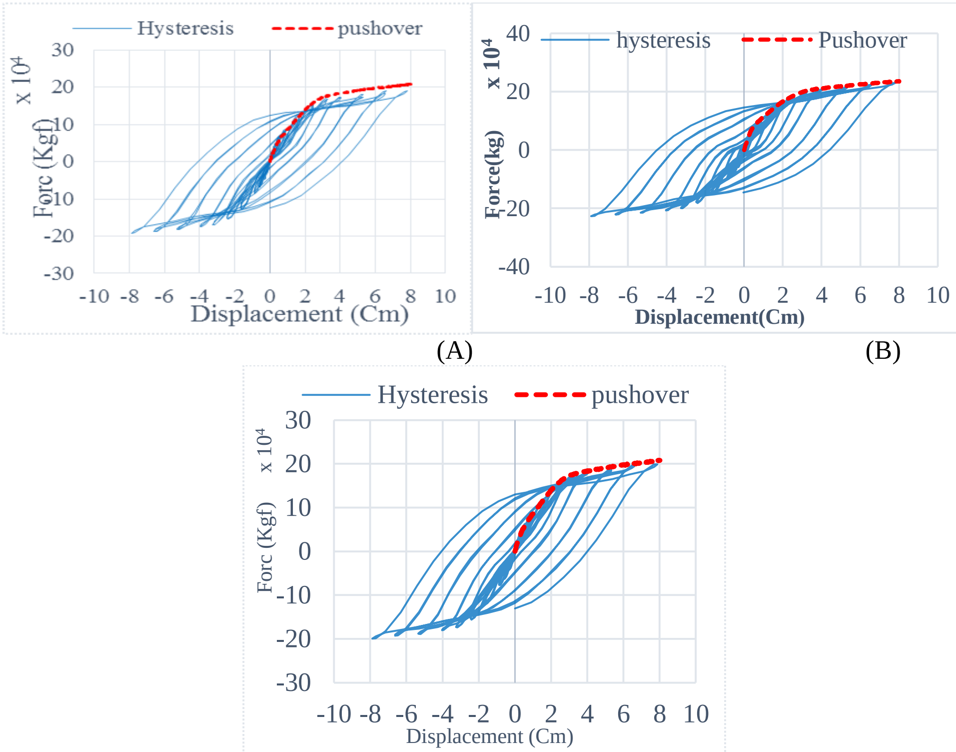
Figure 9. Ultimate limit of proposed models (A) First model (B)Second model(C)Third model.

4.2. Evaluation of Absorbed Energy and Initial Stiffness

One of the most important criteria of evaluation of seismic behavior in a member of the structure is the amount of absorbed energy by that member. This criteria shows the participation of the member in the seismic strength and causes energy attenuation of seismic energy. We can evaluate their cyclic behavior by obtaining the hysteresis graphs of the first and second models. Also, by obtaining the surface of the under hysteresis curve we can obtain the value of absorbed energy. Relation 4-1 is used to obtain the surface of the under the curve.

$$\boldsymbol{u} = \frac{|y2 - y1|}{2} \times |x2 - x1| \qquad (1)$$

As can be seen in the graphs of Figures 10, the amount of force in the defined abutments has been increased to a maximum value of 230000 kilograms in the first model and maximum value of 200000 kilograms in the second and third model and maximum displacement is equal to 8 centimeters. The surface of the under hysteresis curve of the first model is bigger and the amount of absorbed energy in that model is 16% higher.The initial stiffness is a criterion equal to the ratio of yielding strength over the yielding displacement. Considering the fewer amounts of the surface of middle plates in the second and third models relative to the first model, this criteria has been decreased 30% in the second and third models. Table 4-2 shows the absorbed energy and initial stiffness of the three models.



(A) (B)

(C)

Figure 10. Hysteresis graph and push-over (force-displacement) graph of the (A) First model (B) second model (C) Third model.

Table 5. Absorbed energy and initial stiffness in three models.

Model number	Initial stiffness (kg/cm)	Absorbed energy (kgf.cm)
1	153158	27516426
2	108053	23042900
3	98983	24365953

5. Conclusions

Evaluation of seismic behavior of meshy shear walls was performed in this research. In addition to the calibration of modeling following results were obtained:

a- The presence of the plate of the wall increases attenuation energy, considerably.

b- The creation of 17% opening in the steel plate shear wall can impact 15 to 30% in the yielding and ultimate strengths, 16% in the absorbed energy by the wall, around 30% in the initial stiffness.

c- In the case that the area of the opening in the steel plate shear wall is equal in the states of meshy circular and middle rectangular, a noticeable difference does not exist in seismic performance criteria of the wall.

d- Considering the approximate equality of performance of shear walls with an opening in the mentioned states, it can be decided by considering the architectural regulations of the project to use the rectangular opening for the possibility of strengthening using FRP.

e- The effect of distance between holes is more than the effect of diameter of the holes on the results change.

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