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Parametric study of two-layer corrugated steel shear wall under lateral load

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Abstract: Steel shear walls have always been used in the construction and improvement of many structures due to their advantages such as high strength and stiffness, ductility and excellent energy absorption. In the meantime, corrugated steel shear walls have been proposed due to postponing the elastic buckling of the plate and increasing ductility and energy absorption. Corrugated steel shear walls can be used in both single and double layers. Due to the fact that so far, limited research has been conducted about double corrugated steel shear walls, therefore, in this research, the hysteresis behavior of double and single layer corrugated steel shear walls has been analyzed parametrically using the finite element method and using ABAQUS software. Thus, after validating a experimental sample, a two-layer corrugated steel shear wall with one bay-one story with conventional angles of 30, 45 and 60 degrees was investigated in ABAQUS software under cyclic loading. The results of this research showed that the hysteresis curve of double and single layer corrugated steel shear walls is stable. Also, the resistance and energy absorption of double corrugated steel shear walls is higher than single layer corrugated wall. Also, the resistance of corrugated steel shear walls with single and double layers is lower than that of flat steel shear walls. Also, increasing the corrugation angle of the plate has led to an increase in resistance and energy absorption. In addition, behavior factor and ductility of flat steel shear walls are higher than single-layer and double corrugated walls. Nevertheless, the over-strength factor of the studied samples is almost equal to each other. (DOI:**https//doi.org/10.52547/JCER.4.4.51**)

Keywords: Corrugated wall, resistance, energy absorption, seismic coefficients, abacus

1. Introduction

Steel shear wall to deal with the lateral forces of earthquake and wind in buildings, especially in tall buildings, has been considered in the last five decades. The steel shear wall system is a very simple system in terms of implementation and there is no special complexity in it. High resistance, high stiffness, high ductility and stable hysteresis behavior are the main advantages of this system. Steel shear walls without stiffeners have lower strength and energy absorption due to premature buckling of the plate. To overcome this problem, two ways of using hardener and corrugated plate are suggested. So that the use of corrugated plate delays buckling and subsequently increases energy absorption and ductility, another solution that is the use of double corrugated plates. In this thesis, the behavior of double trapezoidal corrugated steel shear walls under cyclic loading will be investigated in ABAQUS

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software. A lot of research has been done on corrugated steel shear walls in the past, some of which are briefly reviewed below. In 2021, Rudsari et al investigated the effect of opening characteristics and plate thickness on the performance of sinusoidal and trapezoidal corrugated steel shear walls [1]. In 2021, Wang et al analyzed the relationship between out-of-plane and in-plane failure of corrugated steel plate shear wall [2]. This paper examines the relationship between out-of-plane stiffness and in-plane stiffness in a frame shear wall with a boundary member including beam and column to achieve full in-plane performance. In 2021, Gohtarian and Melki conducted a numerical study of corrugated steel shear walls with double-layer plate [3]. In this research, things like horizontal or vertical orientation of the corrugated plate, connection of the plate to the columns, thickness of the plate and ratio of plate dimensions were investigated as the main parameters. The results of this research showed that corrugated steel shear walls with double-layer plates have considerable stiffness, resistance and energy dissipation capacity. In 2021, Joharchi et al. investigated the parametric periodic behavior of steel shear walls with corrugated plate [4]. Things such as plate corrugation angle, plate thickness and also the ratio of panel dimensions were investigated in this research. The results of this research showed that increasing the thickness of the plate led to an increase in stiffness, energy absorption and resistance. In addition, the effect of the corrugation angle of the plate depends on the thickness of the corrugated plate. In 2020, Behrebar et al investigated the behavior of corrugated steel shear walls with sinusoidal plate under the effect of cyclic loads [5]. In this article, the behavioral performance of sinusoidal corrugated steel shear walls with central opening has been investigated. In this research, it was shown that creating an opening and increasing its dimensions leads to a decrease in the performance of the system, which is due to a decrease in the share of the plate in the lateral load. In 2020, Bhorebar et al evaluated and predicted the response of steel shear walls with corrugated plate and beam with reduced section [6]. In this research, it was found that models with a corrugation angle of 45 degrees showed better performance in terms of energy absorption capacity. In 2019, Nouri and Iftikhar investigated numerically the effect of the shape and location of the opening on the behavior of corrugated steel shear walls [7]. Kalantari and KalatJari in 2019 investigated the seismic performance of the proposed new system of steel shear wall composed of smooth and corrugated plates [8]. In 2018, Fazel et al investigated the effect of plate corrugation angle and its direction on the performance of corrugated steel shear walls [9]. In 2018, Wang et al investigated the seismic performance of composite steel shear walls with corrugated plate [10]. Caio and Huang in 2018 investigated the laboratory and numerical simulation of steel shear walls subjected to cyclic loads [11]. In 2018, Deva et al investigated the shear strength and post-buckling behavior of corrugated steel shear walls [12]. This paper has carried out numerical investigations on the behavior of lateral resistance and the design of corrugated infill plates in steel shear walls under uniform lateral shear force. In 2018, Qi et al investigated the laboratory behavior of corrugated steel shear walls [13]. Three corrugated walls and one wall with a flat plate were tested in this research. The bearing capacity of the wall with flat plate is higher than the wall with corrugated plate. This is despite the fact that the initial stiffness of the flat wall was lower than that of the wavy walls. In 2018, Tong and Gu investigated the behavior of corrugated steel shear walls containing hardener [14]. The results of this research showed that the presence of hardeners has been able to significantly prevent buckling out of the wall plane. It has also been able to increase the carrying capacity and plasticity. In 2017, Ding et al investigated the effects of opening on the behavior of trapezoidal corrugated steel shear walls [15]. In this article, in general, all the samples studied in this research showed good deformation capacity and plasticity. The results of this research also showed that the initial stiffness of the wall without openings is higher than the samples with openings. Also, the energy absorption of the sample without opening is less than the sample with opening. The cyclic behavior of corrugated steel shear walls with sinusoidal plate was investigated in 2017 by Zhao et al. [16]. The results of this research showed that the energy absorption, strength and initial stiffness of corrugated steel shear walls with a large depth are 26, 5 and 34% higher, respectively, compared to a simple plate shear wall. Meanwhile, the bearing capacity of a flat wall is 25% higher than that of corrugated walls with a shallow depth. The direction of placing the corrugated plate inside the panel also has a small effect on the behavior of the sinusoidal corrugated walls. In 2017, Noor Alizadeh et al investigated the behavior of smooth steel shear walls reinforced by corrugated plates [17]. The results of this research showed that the maximum shear capacity of steel shear wall reinforced with corrugated plate is on average 31% higher than smooth steel shear walls. Also, the use of corrugated plate in the whole panel has no effect on preventing the buckling of the flat plate, and therefore it is not recommended to use the corrugated plate as a reinforcement in the whole panel. In 2017, Shun et al. experimentally investigated the cyclic behavior of corrugated steel shear frames [18]. The results of this research showed that the way of placing the corrugated plate horizontally or vertically inside the panel does not have much effect on the cyclic behavior of the corrugated walls. Hosseinzadeh et al investigated the behavior of corrugated steel shear walls in a laboratory in 2017 [19]. The main variable in this research was the plate corrugation angle. In this research, it was observed that by reducing the corrugation angle of the plate, the initial stiffness, load capacity and energy absorption increased. However, no significant relationship was found between the ductility coefficient and the corrugation angle of the plate. In 2016, Yoo and Yoo investigated the behavior of cold-rolled steel shear walls containing circular openings [20]. In this research, it was found that cold-rolled corrugated shear walls without opening have significantly high initial strength and stiffness, but they have poor ductility under cyclic loading. In 2013, Emami et al investigated the seismic performance of simple and corrugated steel shear walls [21]. The results of this research showed that the initial stiffness of walls with corrugated plates is higher than that of plain walls. Also, the bearing capacity of samples with corrugated plate is less than that of a simple wall. Corrugated plate samples showed up to 6% relative displacement and plain wall sample up to 5% relative displacement.

2. Research method

In this research, ABAQUS software will be used to model the studied samples. First, a one-story-one-bay steel shear wall frame with a flat plate was designed using Guide No. 20 of the AISC341 regulation, which is specific to steel shear walls, and then under cyclic loading, its hysteresis behavior was studied and the parameters of strength, stiffness and energy absorption were investigated. And also the seismic coefficients will be extracted. In the next step, behavior of single and double corrugated steel shear walls with the corrugation angle of 30, 45 and 60 degrees was studied. It should be noted that in order to investigate the effects of the thickness of the corrugated plate, three thicknesses of 2, 4 and 6 mm considered. ATC24 loading protocol has been used to study the cyclic behavior of the samples. The images of single-layer and double-layer corrugated wall sections are shown in figures 1 and 2, respectively:

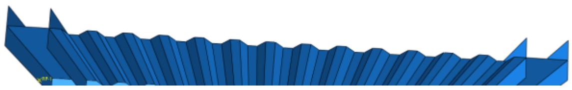

Figure (1) cross-section of a single-layer corrugated wall

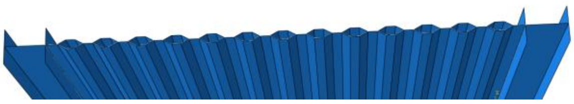

Figure (2) cross-section of a double-layer corrugated wall

3. Validation

In this section, the validation results are presented. The intended validation is related to the laboratory work of Emami et al., which is a corrugated steel shear wall sample [21]. They used the plate in figure 3 as a trapezoidal corrugated plate.

Figure (3) dimensions and wave geometry in corrugated steel shear wall [21]

Dynamic implicit method was used for cyclic analysis in ABAQUS software. In the application section. The hysteresis curve obtained from the finite element analysis along with the laboratory results is also shown in Figure 4. As can be seen in the figure, there is a very good agreement between the experimental results and the finite element analysis.

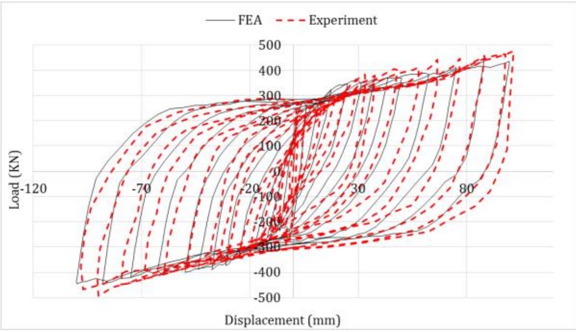

Figure (4) load-displacement curve of FE and test models

4. Modeling considerations in ABAQUS software

S4R type shell element has been used to model flat, corrugated plate and other members. Structured meshing technique has been used for various members of corrugated steel shear wall. In order to analyze the behavior of the studied samples in ABAQUS software, implicit dynamic analysis method has been used. In order to connect the infill plates to the boundary members including beams and columns, the tie option in the interaction module was used in ABAQUS software. it should be mentioned that the behavior of the steel used in the materials module in the strain hardening of Combined

5. Specifications of the studied samples

The geometric specifications of the studied frame are presented in Table 1. It should be mentioned that the I-shaped section is used for the beam and column members. d, bf, tf and tw in the mentioned tables mean height, flange width, flange thickness and web thickness, respectively. The height of all floors is 3200 mm and the width of the frame is 5600 mm. It should be mentioned that ordinary steel St37 has been used for beam, column and plate members. The yield and ultimate stress of this steel were considered to be 240 and 360 MPa, respectively.

6. behavior of the studied samples

6.1. behavior of samples with a plate thickness of 2 mm

Figures 5 to 7 show the hysteresis curves of samples with a plate thickness of 2 mm

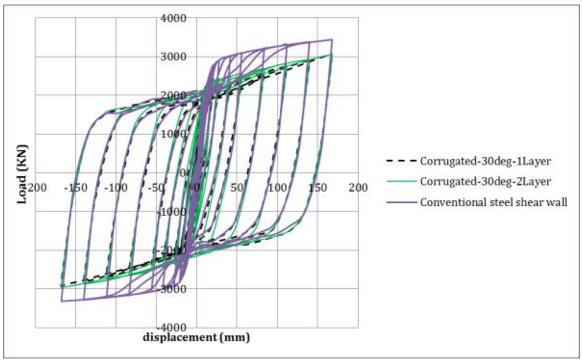

Figure (5) hysteresis curve of samples with a corrugation angle of 30 degrees and a plate thickness of 2 mm

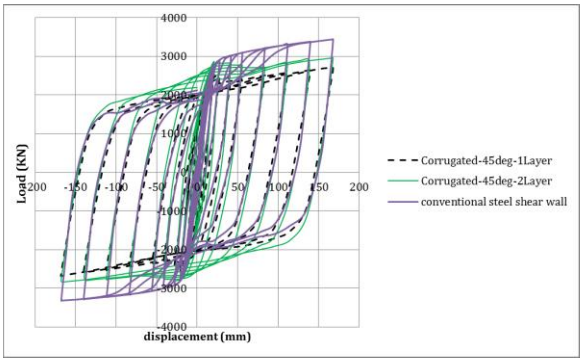

Figure (6) hysteresis curve of samples with a corrugation angle of 45 degrees and a plate thickness of 2 mm

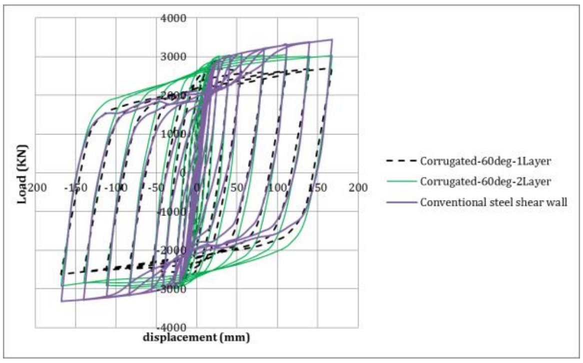

Figure (7) hysteresis curve of samples with a corrugation angle of 60 degrees and a plate thickness of 2 mm

Table 1 shows the maximum resistance values of corrugated and plain wall samples with 2 mm plate thickness. As can be seen, the resistance of corrugated walls with a 30-degree angle with single and double plate with a thickness of 2 mm is lower by 11.8% and 10.9%, respectively, than the flat steel shear wall. The resistance of corrugated walls with a 45 degree angle with single and double plates is lower than flat steel shear wall by 21.3 and 13.9 percent, respectively. Also, the resistance of single and double corrugated walls with an angle of 60 degrees is lower than flat steel shear wall by 14.6% and 11.6%, respectively. Another result is that, the resistance of the double corrugated wall with angles of 30, 45 and 60 degrees is 1, 9.4 and 3.6% higher than the single layer corrugated wall, respectively.

Table 1
Resistance of corrugated and plain wall samples with 2 mm plate thickness

sample	corrugation angle (degree)		
	30	45	60
2-layer corrugated steel shearwall	3 066	2 963	3 042
1-layer corrugated steel shear wall	3 035	2 707	2 937
Flat steel shear wall	3442		

In Table 2, the energy absorption values of corrugated and flat wall samples with 2 mm plate thickness are presented. The absorbed energy of the single and double layer corrugated steel shear wall with a corrugation angle of 30 degree is lower by 10.8 and 1.3 percent, respectively, compared to the flat steel shear wall. The absorbed energy of the double corrugated wall with a corrugation angle of 45 degrees is 11.8% more than the flat steel shear wall. Meanwhile, the energy absorbed by the single-layer corrugated wall is 4.6% less than the simple steel shear wall. The absorbed energy of single and double corrugated walls with an angle of 60 degrees is more than the simple steel shear wall by 1.5 and 20.5%, respectively. Single layer is 10.6%, 19.5% and 18.7% respectively.

Table 2
Absorbed energy in corrugated and flat walls samples with 2 mm plate thickness

sample	corrugation angle (degree)		
	30	45	60
2-layer corrugated steel shearwall	4468	5065	5458
1-layer corrugated steel shear wall	4039	4237	4598
Flat steel shear wall	4529		

6.2. Behavior of samples with a plate thickness of 4 mm

Figures 8 to 10 show the hysteresis curves of samples with a plate thickness of 4 mm.

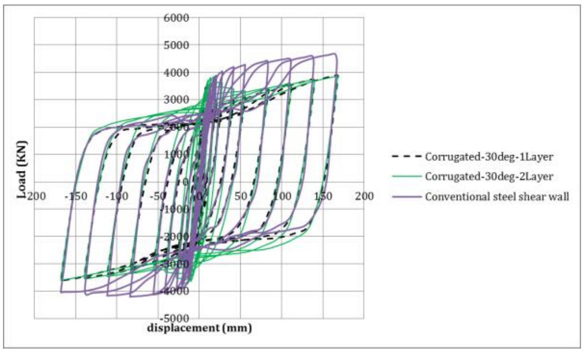

Figure (8) hysteresis curve of samples with a corrugation angle of 30 degrees and a plate thickness of 4 mm

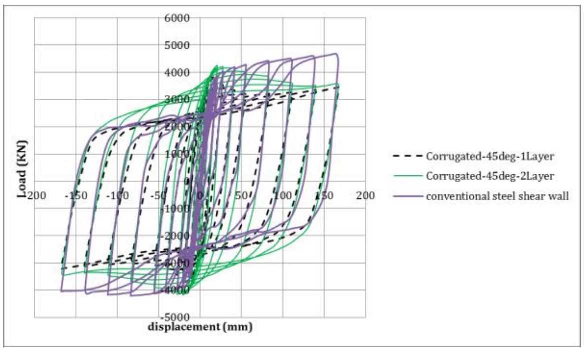

Figure (9) hysteresis curve of samples with a corrugation angle of 45 degrees and a plate thickness of 4 mm

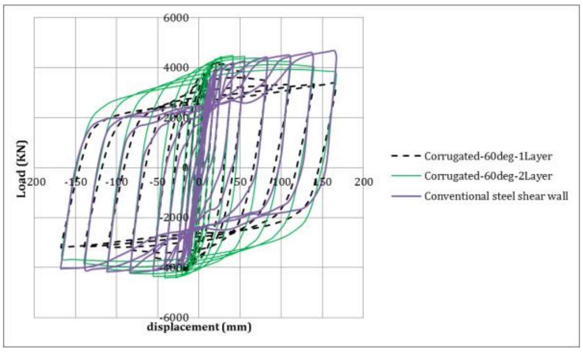

Figure (10) hysteresis curve of samples with a corrugation angle of 60 degrees and a plate thickness of 4 mm

Table 3 shows the maximum resistance values of corrugated and flat wall samples with 4 mm plate thickness. According to the values in Table 4, in the case of steel shear walls with a plate thickness of 4 mm, the results are as follows:

The maximum resistance of single and double layer corrugated steel shear wall with 30 degree corrugation angle is lower by 16.4% and 16.8% respectively compared to flat steel shear wall. The resistance of corrugated walls with a 45 degree angle with single and double plates is 16.7% and 8.9% less than flat steel shear wall, respectively. Also, the resistance of single and double corrugated walls with an angle of 60 degrees is lower by 1.8 and 1.4 percent, respectively, compared to flat steel shear wall. The resistance of the double corrugated wall with angles of 45 and 60 degrees is higher than the single layer corrugated wall by 9.4% and 4.3%, respectively. The resistance of the double corrugated wall with an angle of 30 degrees is 0.4% less than the single layer corrugated wall.

Table 3
Strength of corrugated and simple wall samples with 4 mm plate thickness

sample	corrugation angle		
	30	45	60
2-layer corrugated steel shear wall	3884	4254	4477
1-layer corrugated steel shear wall	3901	3889	4292
Flat steel shear wall	4670		

Table 4 shows the energy absorption values of corrugated and plain wall samples with 4 mm plate thickness. The absorbed energy of the double corrugated wall with a corrugation angle of 30 degrees is 10.9% more than the simple steel shear wall. Despite this, the absorbed energy of the single-layer corrugated wall is 1.8% lower than that of the simple steel shear wall. The absorbed energy of the double corrugated wall with a corrugation angle of 45 degrees is 24% more than that of the simple steel shear wall. The absorbed energy of the single-layer corrugated wall is 3.8% less than the simple steel shear wall. The absorbed energy of the double and single layer corrugated wall with a corrugation angle of 60 degrees is 10% and 41% higher than the simple steel shear wall, respectively. The absorbed energy in double corrugated walls with angles of 30, 45 and 60 degrees is 21, 28 and 27% higher than single layer corrugated wall, respectively.

Table 4

Absorbed energy in corrugated and flat wall samples with 4 mm plate thickness

sample	corrugation angle		
	30	45	60
2-layer corrugated steel shearwall	4468	5065	5458
1-layer corrugated steel shear wall	4039	4237	4598
Flat steel shear wall	4529		

6.3. Behavior of samples with a plate thickness of 6 mm

Figures 11 to 13 show the hysteresis curves of samples with a plate thickness of 6 mm.

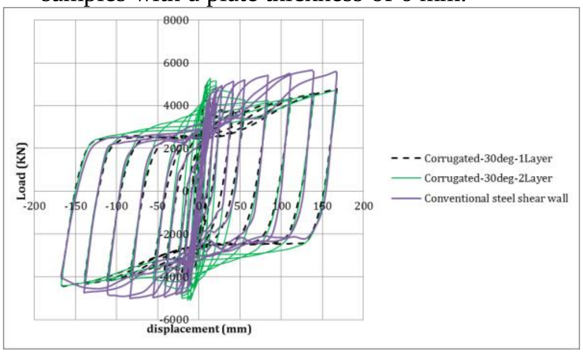

Figure (11) hysteresis curve of samples with a corrugation angle of 30 degrees and a plate thickness of 6 mm

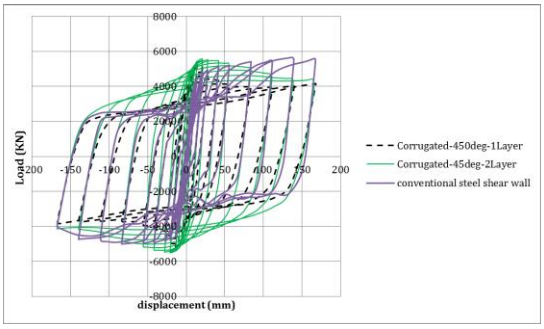

Figure (12) hysteresis curve of samples with a corrugation angle of 45 degrees and a plate thickness of 6 mm

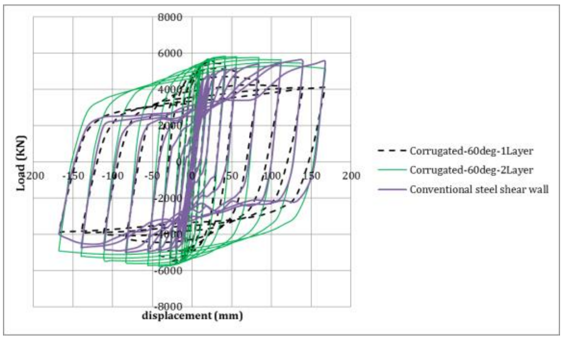

Figure (13) hysteresis curve of samples with a corrugation angle of 60 degrees and a plate thickness of 6 mm

In table 5, the maximum resistance values of corrugated and flat wall samples with 6 mm plate thickness are presented. According to the values in Table 6, in the case of steel shear walls with a plate thickness of 6 mm, the results are as follows:

•The maximum strength of single and double layer corrugated steel shear wall with 30 degree corrugation angle is lower by 12.6% and 6.75% respectively compared to plain steel shear wall.

•The resistance of corrugated walls with a 45-degree angle with single and double plates is 4.5% and 1.3% less than plain steel shear wall, respectively.

•The resistance of a single-layer corrugated wall with a 60-degree angle is 0.15% less than a simple steel shear wall. Meanwhile, the double corrugated wall is 2.3% more than the simple steel shear wall.

The resistance of the double corrugated wall with angles of 30, 45 and 60 degrees is higher than the single layer corrugated wall by 6.7%, 4.3% and 3.4% respectively.

Table 5

Strength of corrugated and simple wall samples with 6 mm plate thickness

Sample	Corrugation angle (degree)		
	30	45	60
2-layer corrugated steel shearwall	5274.92	5580.87	5839.94
1-layer corrugated steel shear wall	4944.33	5347.56	5648.34
Flat steel shear wall	5657.18		

In Table 6, the energy absorption values of corrugated and plain wall samples with 6 mm plate thickness are presented.

•The absorbed energy of the double corrugated wall with a corrugation angle of 30 degrees is 13% more than the simple steel shear wall. Despite this, the absorbed energy of the single-layer corrugated wall is 3.8% lower than that of the plain steel shear wall.

•The absorbed energy of the double and single layer corrugated wall with a corrugation angle of 45 degrees is 1 and 35% higher than the simple steel shear wall, respectively.

•The absorbed energy of the double and single layer corrugated wall with a corrugation angle of 60 degrees is 18% and 57% higher than the simple steel shear wall, respectively.

•The absorbed energy in double corrugated walls with angles of 30, 45 and 60 degrees is 23, 34 and 32% higher than the single layer corrugated wall, respectively.

Table 6
Strength of corrugated and simple wall samples with 6 mm plate thickness

Sample	Corrugation angle (degree)		
	3 0	4 5	60
2-layer corrugated steel shearwall	7944	9553	11038
1-layer corrugated steel shear wall	6445	7092	8326
Flat steel shear wall	7030		

7. Seismic coefficients of the studied samples

Tables 8 to 10 show the values of seismic coefficients in corrugated and plain wall samples with plate thickness of 2, 4 and 6 mm. As stated in the mentioned tables, the values of behavior coefficients and plasticity of smooth steel shear walls are higher than single and double layer corrugated walls. Nevertheless, the added resistance factor of the studied samples is almost equal to each other.

8. Conclusion

The results of the numerical modeling done in this thesis are as follows:

ABAQUS software has a remarkable ability to predict the behavior of corrugated steel shear wall.

o The values of coefficients of behavior and plasticity of smooth steel shear walls are higher than single and double layered corrugated walls. Nevertheless, the added resistance factor of the studied samples is almost equal to each other.

o The resistance of corrugated steel shear walls, both single and double layer, is lower than plain steel shear wall. Only the resistance of the double-layer corrugated wall with a corrugation angle of 60 degrees and a thickness of 6 mm was higher than that of the plain wall.

o The resistance of double-layer corrugated steel shear walls is higher than that of single-layer corrugated steel shear walls.

o Energy absorption of double-layer corrugated steel shear wall is more than plain steel shear wall.

o Energy absorption of double-layer corrugated steel shear wall is more than single-layer corrugated steel shear wall.

o Increasing the angle of the corrugated plate has increased the strength and energy absorption of the single and double layer corrugated steel shear wall.

Acknowledgments

Acknowledgments should be inserted at the end of the paper, before the references, not as a footnote to the title. Use an unnumbered section heading for the Acknowledgments, similar to the References heading.

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