

Investigating Seismic Behavior and Analyzing the Nonlinear Behavior of the Corrugated and Flat Steel Shear Walls

Abstract

The use of steel shear walls has always drawn much attention due to their creation of high hardness and strength in metal frames. The present study examines the use of triangular corrugated sheets compared to flat sheets. Although its more expensive in contrast to the flat sheets, the triangular corrugated sheets feature more resistance to buckling and prevent severe stress to concentrate on the frame. Using ABAQUS and laboratory validation results for three flat and corrugated shear walls, the remarkable ability of ABAQUS has been proved again herein for the analysis of steel shear walls. The present study compares sixteen shear wall models with different lengths and amplitudes. The results indicated that the increase in the length and decrease in the corrugation amplitude caused increases in the elastic hardness of the frame. Sheets with 10-centimeter corrugation amplitude and 30-centimeter length outperformed the others and featured buckling resistance of about twice as much as the flat sheets. A comparison of the horizontal and vertical triangular corrugated sheets reflects the idea that the use of column-parallel corrugations can increase the frame's strength. In this research paper, 24 frames with flat and corrugated walls reaching thicknesses of 4mm, 5mm, and 6mm have also been examined in 1-, 2-, 4- and 8-story buildings. The results indicated that the frames made of corrugated sheets behave more favorably compared to the flat sheets and the higher the thickness of the corrugated sheets, the higher the energy dissipation and the higher the frame's strength will increased.

Keywords: *steel shear walls, corrugated sheets, triangular sheets, ABAQUS, sheet's buckling*

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Introduction

The use of shear walls in the buildings was commenced as a proper solution for counteracting the earthquake forces in 1950, simultaneously with the extensive reconstruction activities in the aftermath of WWII. The preliminary efforts for the reinforcement of the buildings were being made based on not so much exact hypotheses and assumptions about the structures' reactions to the land vibrations, and due to the shortage of proper analytical tools and sufficient information on the background and history of earthquakes, they were mostly imperfect method being applied. Empirical and theoretical research done in the world during the 1960s, 1970s, and 1980s led to the compiling of detailed information about the reaction of the building systems equipped with shear walls during earthquakes. These studies emphasized the importance of flexible moment-resisting frames for reducing seismic loads.

Steel shear walls (SSWs) are systems utilized for fighting back against the lateral loads caused by earthquakes and wind. SSWs includes a steel sheet, the edges of which are connected to the beam and columns of a frame. The beam-column connections can take place in a joint or fixed format. The sheet is also plain and simple and strengthened with a stiffener. During the past three decades, the SSWs have drawn much attention to fighting the earthquakes and winds' lateral loads in buildings, particularly high-rise buildings. In contrast to the bracing systems, this system features advantages like no breakage of the connections due to the moderation and distribution of the stresses compared to the stress concentration in the connections braced with beam and column, as well as

the possibility of the sheet's replacement following earthquakes.

Miamura and Akiyama (1977) investigated the monotonic and cyclic behaviors of the SSWs. In their study, the sheets' shear buckling load was considerably lower than their shear yield strength. They concluded that the general displacement-load curve of the SSWs can be obtained from the sum of the displacement-load curves calculated for each filler sheet and frame. Agelidis and Mansell (1982) evaluated using the SSWs reinforced with stiffeners. Thorburn et al. (1983) offered an analytical model to study the non-reinforced SSWs' strength. In their model, known as the "parallel strip model," the shear panels take the form of a set of inclined strap members that can only transfer the tensile forces. Kulak et al. (1999) performed a numerical study on an 8-story building with SSWs to investigate seismic performance.

During the early 1970s, Takahashi et al. (1973) performed a set of numerical and laboratory analytical studies on thin SSWs with stiffeners. These experiments aimed to investigate the behavior of the hardened thin SSWs' systems as an alternative for the concrete shear walls. Chen and Jhang (2006) investigated the behavior of the thin steel shear walls using LYP (low yield point) steel for the filler sheets. The experimental results indicated that the early yield of the sheet accompanies the use of LYP steel in the filling sheet in contrast to the frame, and this can guarantee the non-failure of the sheet until before the sheet reaches its final strength.

Choi and Park (2008) investigated the cyclic behaviors of the thin SSWs in 3-story buildings. The results indicated that using low-resistant columns with non-compact cross-sections or

using sheets thicker than what has been designed could lead to creating plastic joints at the foot of the walls. The effect of the corrugation density has been examined on the SSWs by Gholizadeh and Yadollahi (2011). Their results indicated that the increase in the corrugation density could increase the system's hardness and make the load-bearing capacity and energy depreciation show ascending trends.

The present study generally aims at investigating the seismic behaviors of SSWs with flat and corrugated sheets and analyzing the nonlinear behaviors of the elements in ABAQUS's finite element software so that it can become clear how would these SSWs behave under earthquake conditions with various states and different magnitudes and that what would be the thickness required for the establishment of increasingly higher strength in the SSWs. To study the behavior of the SSWs, the pushover method of the ABAQUS application will be utilized, and it is using this program that the

Table (1): specifications of various elements in the laboratory specimens

Specimens	Beam	Column	Plate thickness (mm)	L/t (mm)	h _s /t (mm)	Type panel
No. 1	HE-B140	HE-B160	1.25	1600	1200	Unstiffened
No. 2	HE-B140	HE-B160	1.25	1600	1200	Vertical corrugated
No. 3	HE-B140	HE-B160	1.25	1600	1200	Horizontal corrugated

After modeling and analyzing the models in ABAQUS, the results can be interpreted in Table (2), which also presents the maximum load-bearing capacity of the panels with flat and corrugated sheets as drawn on the laboratory tests and program analysis. Corresponding to the Table, the highest load-bearing capacity pertains to the panel with a flat sheet and matches the results from the ABAQUS program. Considering the Table, the

Table 2: Comparing the load-bearing capacity of the shear wall panels based on the laboratory tests and numerical model

	Experimental result V _u (KN)	ABAQUS result V _u (KN)	Error %
SPECIMEN NO. 1	580	589.15	1.6
SPECIMEN NO. 2	590	486.7	2.7
SPECIMEN NO. 3	490	520.94	5.7

statuses of the shear walls will be examined and studied in the course of different shear forces (exerted during earthquakes with various magnitudes). In this method, the load imposed onto the structure would gradually increase based on a given pattern.

Validation:

The laboratory test results obtained in the article "experimental study on cyclic behavior of trapezoidal corrugated steel shear walls" will be used to validate the ABAQUS software results. The article was published by Dr. Mofid et al. (2013) from Industrial Sharif University in the journal of Engineering Structures. This article examines three shear walls with flat and corrugated sheets subject to the software's pushover analysis. Table (1) gives the specifications of the specimens. The sheets are of the trapezoidal corrugated type, and the corrugations have been studied in two directions.

error stemming from the program's analyses and laboratory results is trivial, i.e., at most 6%. The error is very trivial, and considering the abovementioned materials, the modeling has been authentically carried out in ABAQUS; hence it can very well be replaced for laboratory tests for analyzing the shear wall panels.

Figures (1) to (4) demonstrate the pushover diagrams of the laboratory specimens and the three samples made in ABAQUS. Considering the diagrams, it can be stated that the

modeling is highly precise in ABAQUS and that the program can express the behavior of shear wall panels under the impact of seismic forces.

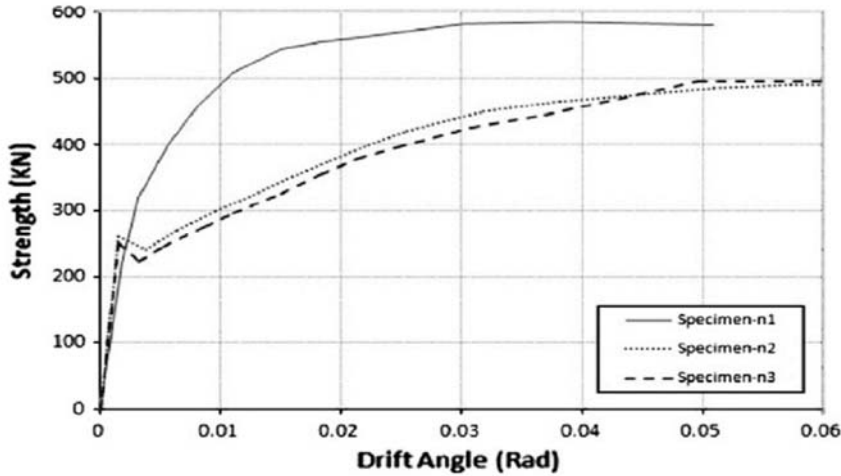


Figure (1): base shear drift diagram (pushover) for the three laboratory specimens

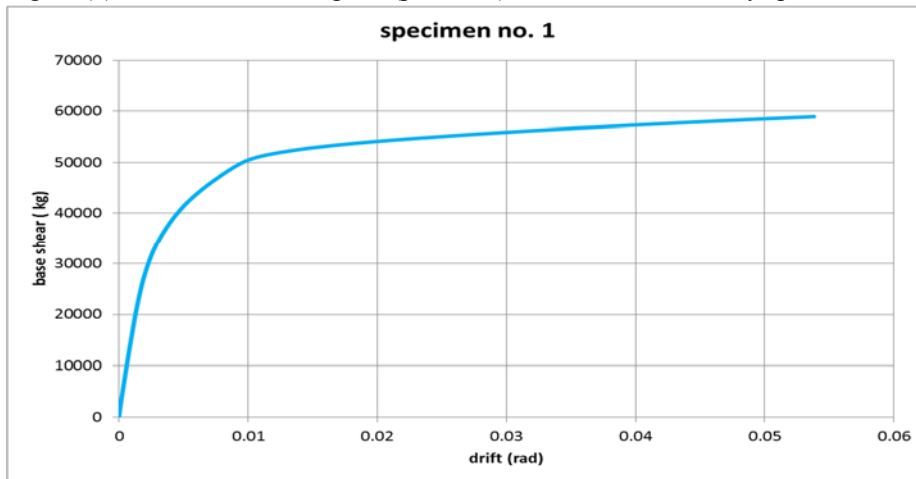


Figure (2): base shear drift diagram (pushover) for the first specimen as obtained in ABAQUS

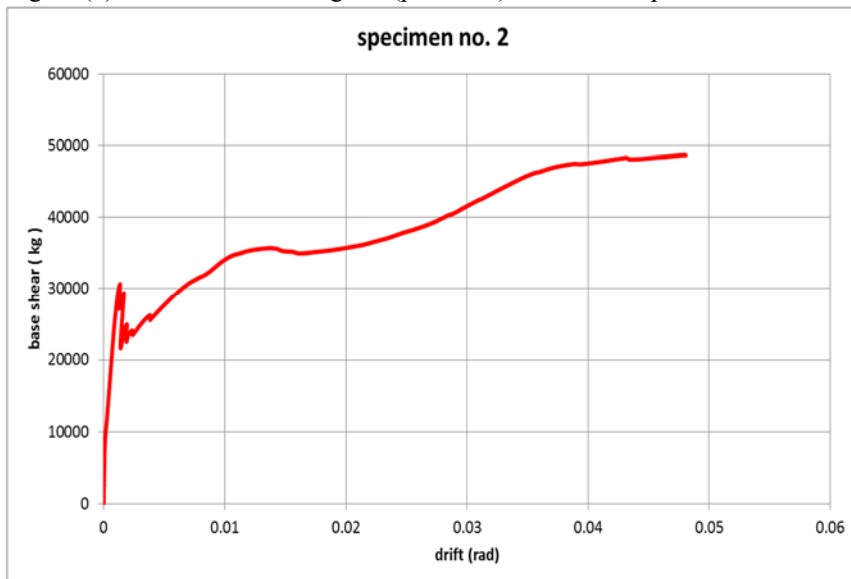


Figure (3): base shear drift diagram (pushover) for the second specimen as obtained in ABAQUS

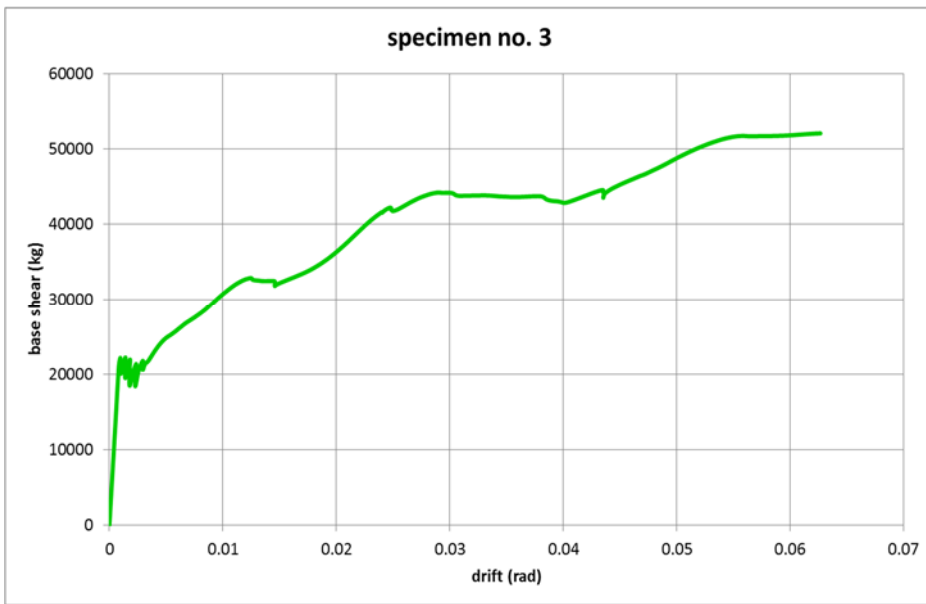


Figure (4): Base shear drift diagram (pushover) for the third specimen as obtained in ABAQUS

Figure (5) illustrates the superimposition of the ABAQUS program's responses and the laboratory results (the diagrams have been superimposed using EXCEL based on an identical and exact scale). Considering the figure, it is clear that the

analytical results obtained in the program are very much similar to the laboratory results and that ABAQUS has been able to perform the analysis of the shear wall panels to match with reality and with a very trivial error.

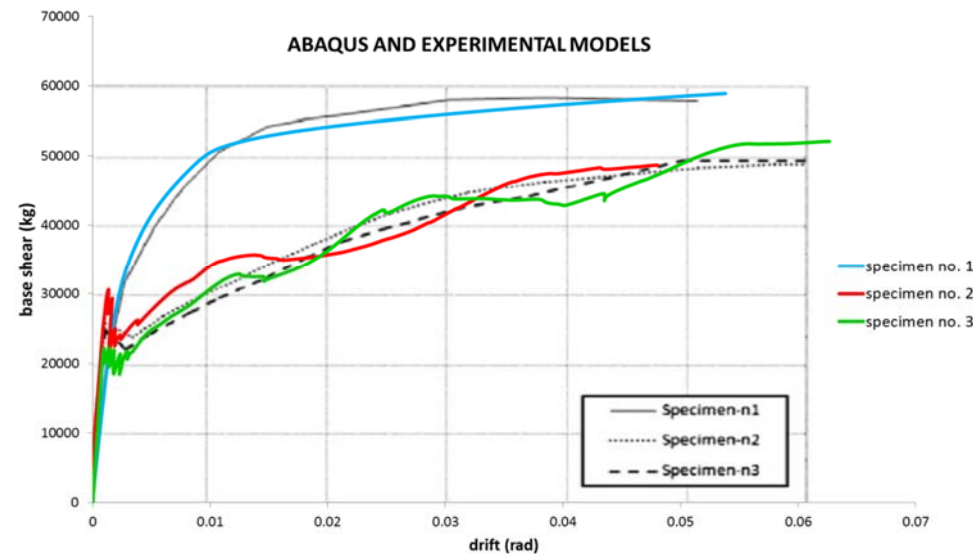


Figure (5): superimposition of the ABAQUS program's responses and laboratory results

Study Method:

Triangular shear wall models were constructed for 1-, 2-, 4- and 8-story buildings with 4mm, 5mm, and 6mm thicknesses in ABAQUS, and the nonlinear static analysis or pushover test was carried out. The load imposed onto the panels was ascending in terms of type and exerted in triangular form onto the surface level of every frame. In the first section, the optimization of the SSW with a triangular frame was carried out under various corrugation lengths and amplitudes and

compared to the flat and corrugated SSWs. In the second section, the models' static analysis or pushover test was conducted concerning the number of stories and various thicknesses of the triangular sheet and compared the flat and corrugated SSWs.

The steel used for the analysis of the models in this dissertation has been selected based on the standards of steel production in Iran.

Table 3: Specifications of the mild steel used herein

Unit volume weight (kg/m ³)	Poisson coefficient	Elasticity module (kg/cm ²)
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7850	0.3	2100000
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In this study and as shown in figure (6), panels with a 2.8-meter span and height have been used to investigate the effects of the

corrugation length and amplitude on the behavior of the shear wall with triangular corrugated sheets.

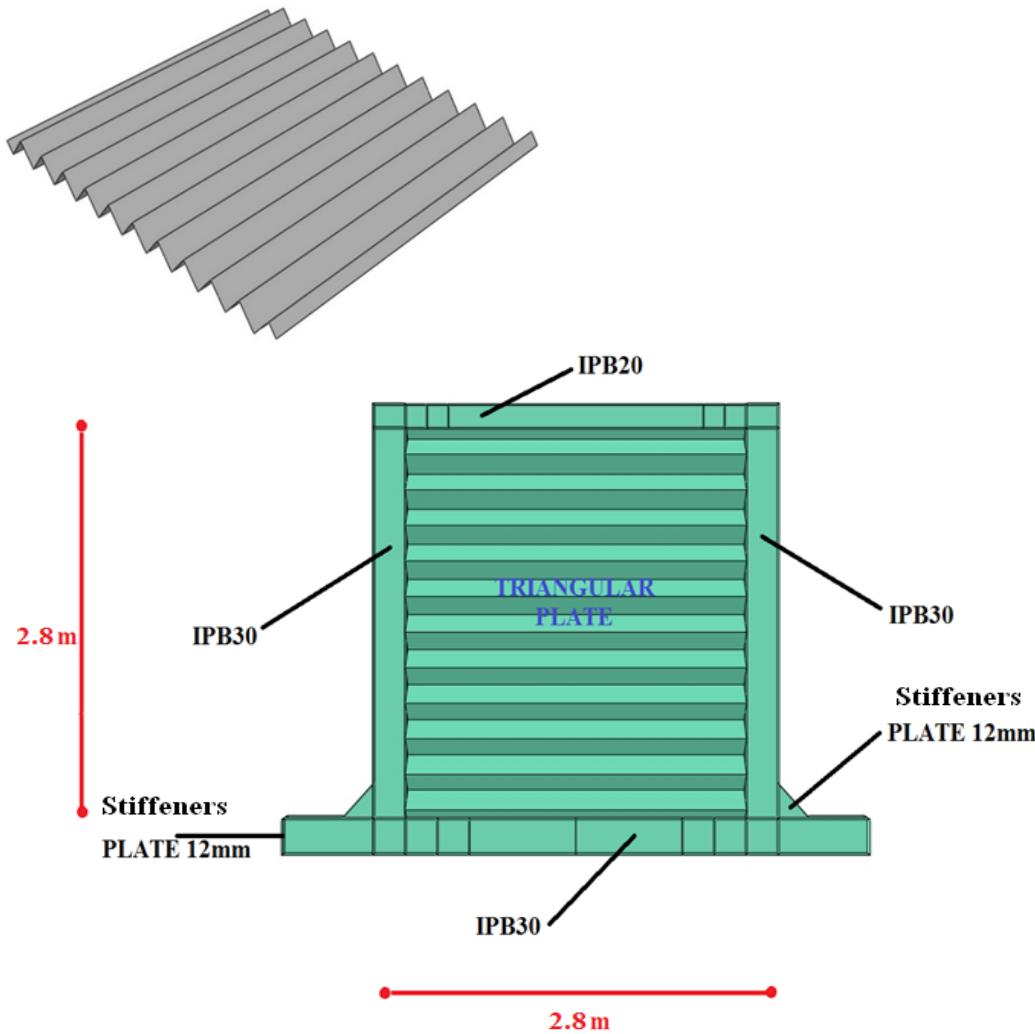


Figure (6): geometrical parameters and specifications of the cross-sections for the single-span panels in the SSWs with triangular sheet. To analyze the models, pushover has been the method of choice. Based on this method, the shear load from the earthquake is imposed on every story onto the top section of the shear wall's panel. The program increases the imposed load consecutively to the extent that the model enters a nonlinear phase and undergoes instability. The load on the 2-, 4- and 8-story models have been triangular.

Considering the engagement of the level beams of the buildings with the buildings' roofs, it is logical to prevent the lateral displacement of the beams on top of the shear wall panels along the axis vertical to the panel surface. Moreover, since the models are two-dimensional, no load is imposed on

the panel's surface along the vertical axis. The meshes are 5cm for the panels of the shear walls.

Findings:

1. The Effect of the Corrugation Length and Amplitude on the Performance of the Triangular Corrugated Shear Steel Wall:

Considering Table (3), sixteen sheets with various corrugation lengths and amplitudes have been used. The models have been named in this section to match the first column of Table (3), with TRI being an abbreviation for triangular, the first number being indicative of amplitude, and the second designating the sheets' length corrugation. It is worth mentioning that all of the sheets in this section are five milliliters in thickness.

Table 3: defining the corrugation length and amplitude for the triangular corrugated sheets

Name	a	b
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TRI-5-10	5cm	10cm
TRI-10-10	10cm	10cm
TRI-15-10	15cm	10cm
TRI-20-10	20cm	10cm
TRI-5-20	5cm	20cm
TRI-10-20	10cm	20cm
TRI-15-20	15cm	20cm
TRI-20-20	20cm	20cm
TRI-5-30	5cm	30cm
TRI-10-30	10cm	30cm
TRI-15-30	15cm	30cm
TRI-20-30	20cm	30cm
TRI-5-40	5cm	40cm
TRI-10-40	10cm	40cm
TRI-15-40	15cm	40cm
TRI-20-40	20cm	40cm

Disregarding the welding, the amounts of steel used for the panels of the shear walls designated in all the rows of Table (3) have been demonstrated in figure (7). According to the Table, it can be stated that the use of sheets with corrugation

amplitude to length ratios below 0.5 (the weight of the steel used in contrast to the flat sheet is below 2.3 times) is economically justifiable, but the amount of the used steel is very high for the other sheets (corrugation amplitude to length ratios above 0.5).

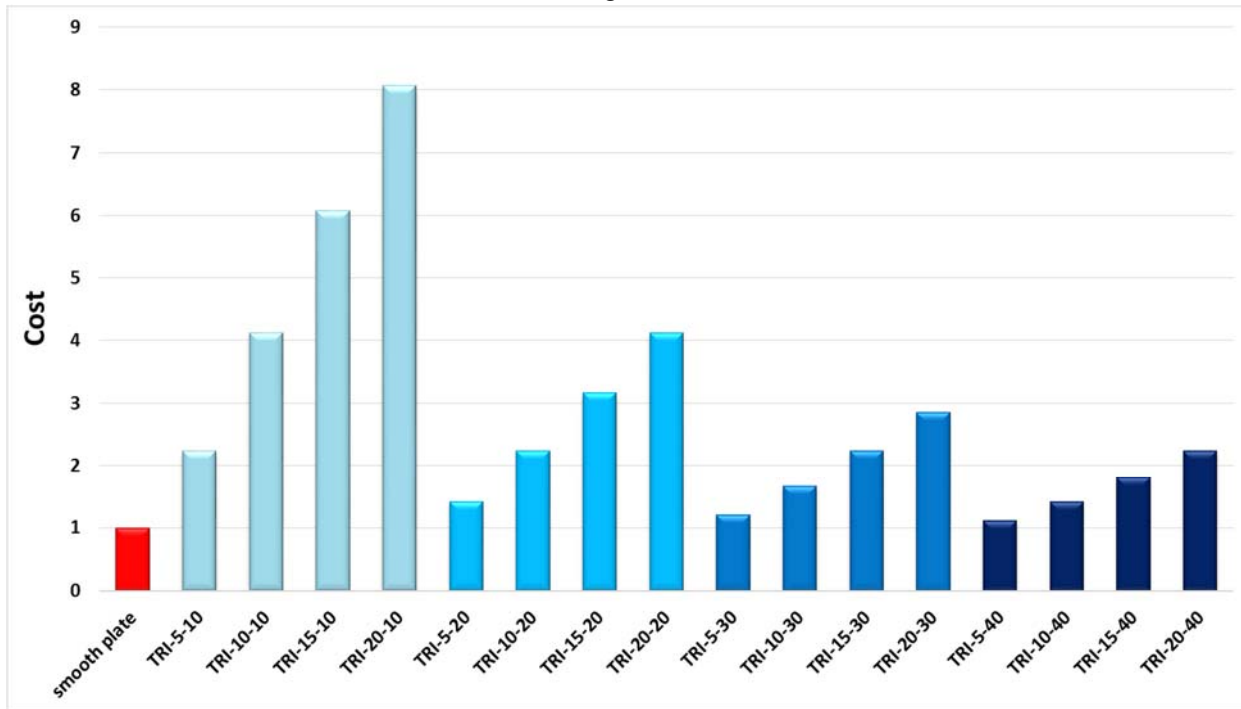


Figure (7): economic comparison of the corrugation length and corrugation amplitude between the triangular corrugated sheets and flat sheets

Figure (8) illustrates the pushover diagram and depreciated energy diagram for all of the states of the shear wall with triangular sheets defined as in table (3). The behaviors of the shear walls are nearly similar for all models in such a way that the shear wall seminally behaves elastically in the beginning

until the load reaches its maximum, after which point a decline in strength appears due to the initiation of buckling. As it was mentioned, in order to select the best performance for a shear wall, as well, both the economic matters and strength issues should be taken into consideration, and, considering these two parameters, the triangular sheet with a corrugation amplitude

of 10 and corrugation length of 30cm seems to be the best performing. In these figures, the black diagram depicts the pushover diagram and the depreciated energy diagram for the TRI-10-30 model. As understood from the figure, the foresaid model behaves better than the other models (proper shear strength, lower strength decline after the sheet's buckling,

higher energy absorption, higher elastic stiffness, suitably used steel, and ease of welding the triangular sheet to the peripheral elements). Corresponding to figure (9), the weight of this type of corrugated sheet is 1.67 times the flat sheet, and compared to the other types of triangular sheets, it features better conditions in terms of economic matters.

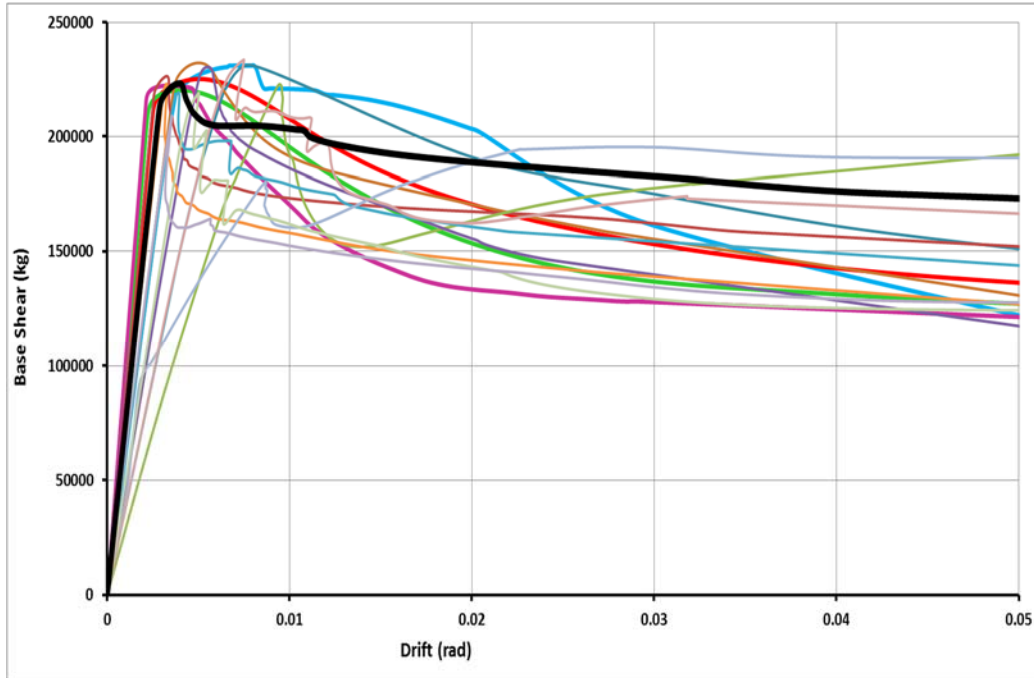


Figure (8): pushover diagram of all the frames with triangular sheets per various corrugation lengths and corrugation amplitudes

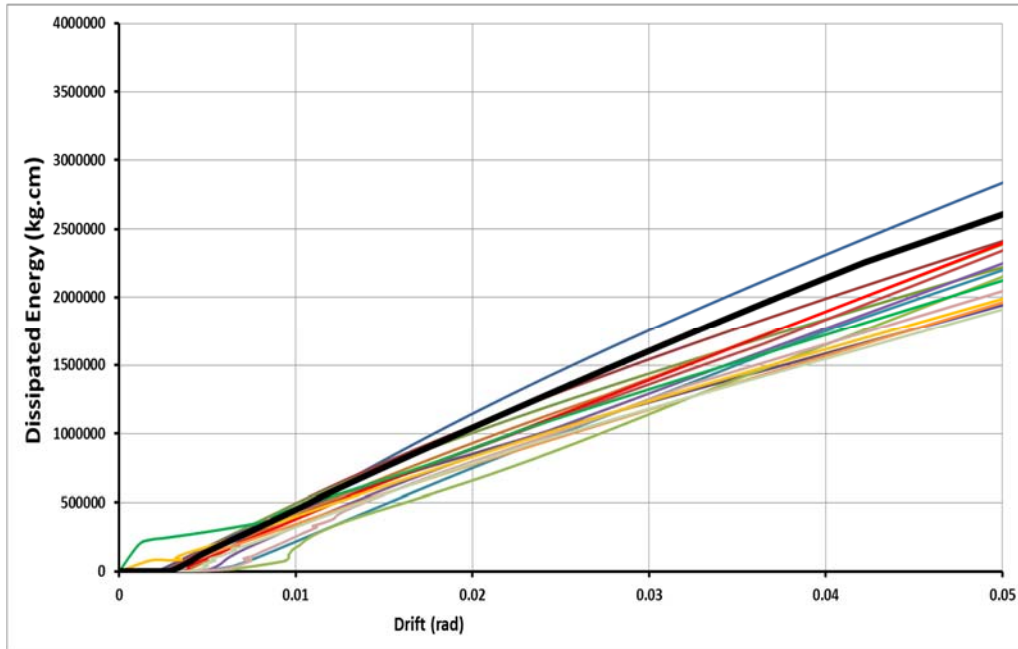


Figure (9): energy dissipation diagram of all the frames with triangular corrugated sheets per various corrugation amplitudes and lengths

2. Investigating the Effect of the Thickness and Number of the Floors on the Behaviors of the Shear Walls with Triangular Corrugated Sheets:

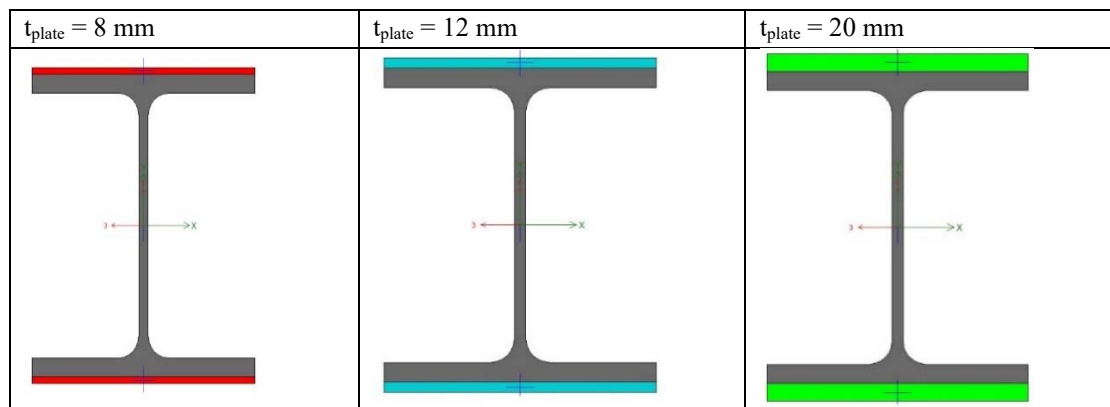
To investigate the shear walls, the best state of the corrugated triangular sheet is when the corrugation amplitude is 10cm and the corrugation length is 30cm. Therefore, these same numbers of corrugation length and amplitude have been applied to

investigate the effect of thickness and floors. In this section, the triangular corrugated sheets and flat sheets will be investigated and compared with thicknesses of 4mm, 5mm, and 6mm. to investigate the effect of the floors, as well, four types of flat and corrugated shear walls have been utilized for 1-, 2-, 4- and 8-story buildings. Table (4) gives the characteristics of the models constructed in ABAQUS. The

models have been named in such a way that the first letter is expressive of the type of the sheet, namely flat or corrugated (horizontally or vertically corrugated), the second letter denotes the number of floors, and the third letter designates the thickness of the sheet. Therefore, 28 models have been constructed in ABAQUS and will be discussed and examined in the upcoming sections.

Table 4: naming the models of the flat and corrugated SSWs based on their thicknesses and number of stories

#	Name	Panel type	Number of storeys	Thickness
1	S14	Smooth	1	4mm
2	S15	Smooth	1	5mm
3	S16	Smooth	1	6mm
4	S24	Smooth	2	4mm
5	S25	Smooth	2	5mm
6	S26	Smooth	2	6mm
7	S44	Smooth	4	4mm
8	S45	Smooth	4	5mm
9	S46	Smooth	4	6mm
10	S84	Smooth	8	4mm
11	S85	Smooth	8	5mm
12	S86	Smooth	8	6mm
13	TH14	Triangular - Horizontal	1	4mm
14	TH24	Triangular - Horizontal	2	4mm
15	TH44	Triangular - Horizontal	4	4mm
16	TH84	Triangular - Horizontal	8	4mm
17	TV14	Triangular - Vertical	1	4mm
18	TV15	Triangular - Vertical	1	5mm
19	TV16	Triangular - Vertical	1	6mm
20	TV24	Triangular - Vertical	2	4mm
21	TV25	Triangular - Vertical	2	5mm
22	TV26	Triangular - Vertical	2	6mm
23	TV44	Triangular - Vertical	4	4mm
24	TV45	Triangular - Vertical	4	5mm
25	TV46	Triangular - Vertical	4	6mm
26	TV84	Triangular - Vertical	8	4mm
27	TV85	Triangular - Vertical	8	5mm
28	TV86	Triangular - Vertical	8	6mm



$I_{33} = 59504 \text{ cm}^4$

$I_{33} = 68168 \text{ cm}^4$

$I_{33} = 86610 \text{ cm}^4$

Figure (10): columns used for modeling the walls with 4mm, 5mm, and 6mm thicknesses

Figures (11) and (12) display the pushover and depreciated energy diagrams for the frames made in one-story buildings for shear wall thicknesses of different rates. According to the figures, it can be stated that the corrugated triangular and flat SSWs behave differently in such a way that the flat walls still show increasing strength after the sheet's buckling, and their pushover diagrams are linear until they start extra-plate buckling. Afterward, the diagram is stretched with a milder

slope and in a curve form. The one-story building's shear wall with flat and corrugated sheets shows higher strength per sheet with larger thicknesses, as shown in figure (11). Energy depreciation is higher in the wall with a corrugated triangular sheet, 6mm in thickness, compared to the other sheets used in the walls and its energy depreciation is a lot more different from the flat sheet of the same thickness.

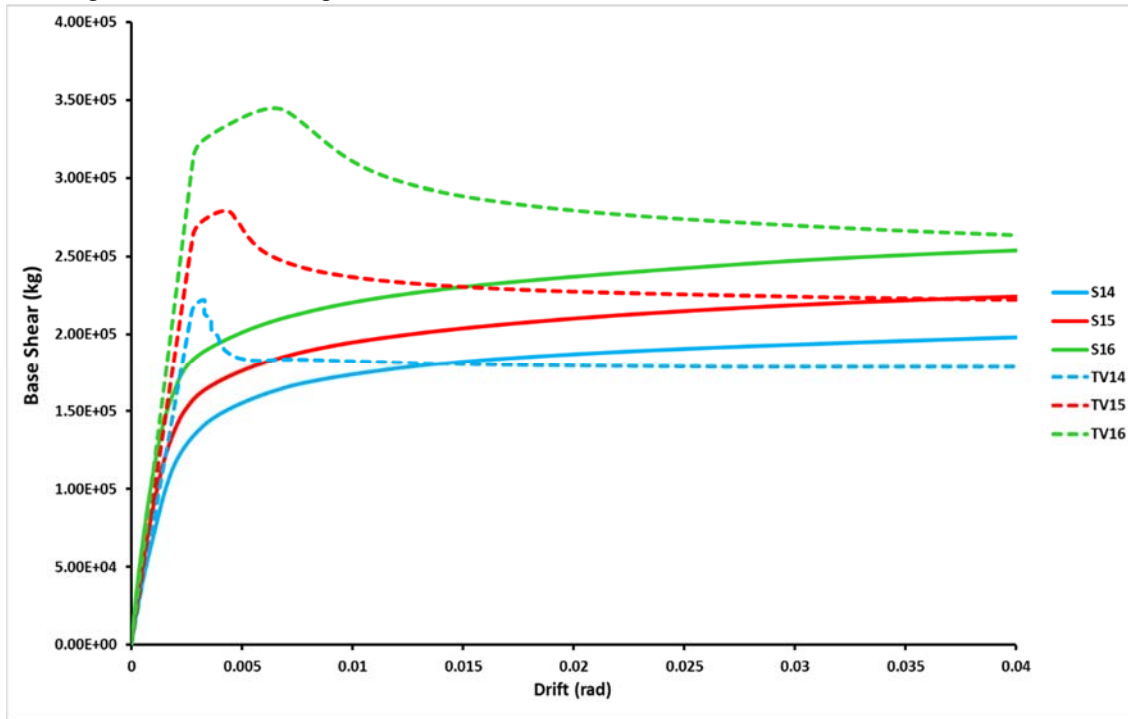


Figure (11): comparing the pushover diagrams of the frames used in one-storey building's flat and corrugated shear walls but with different thicknesses

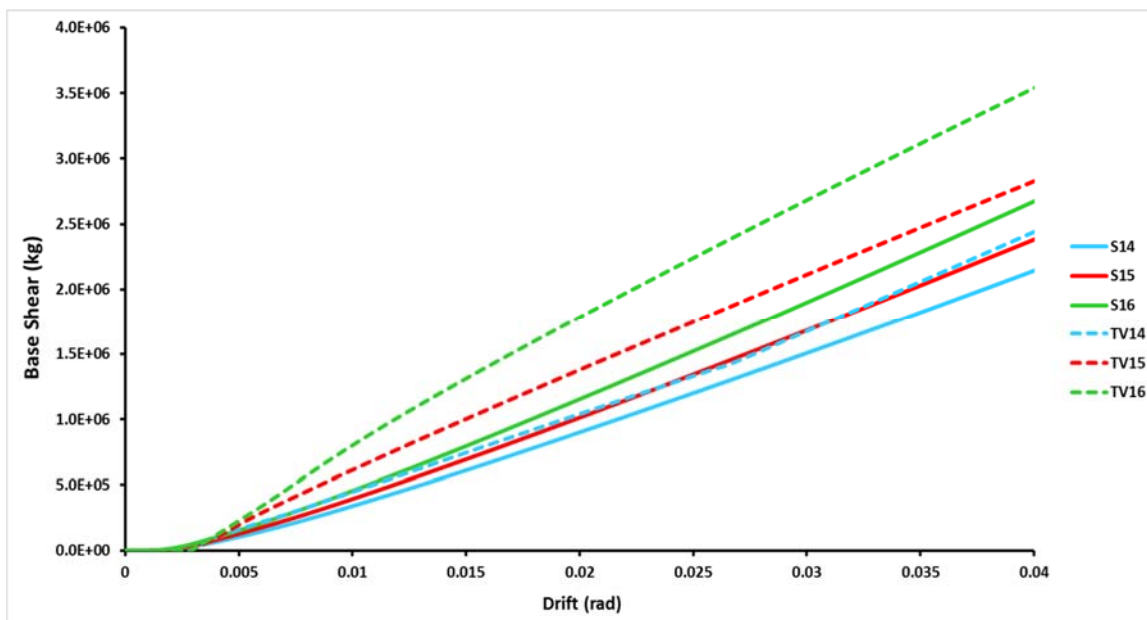
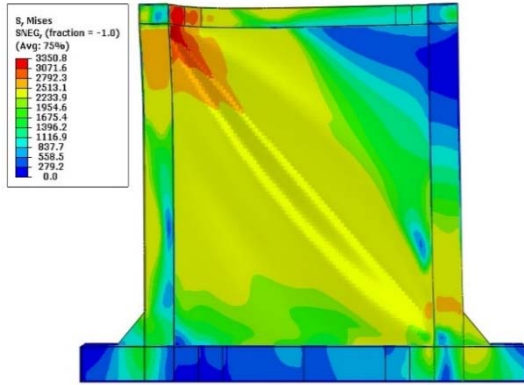


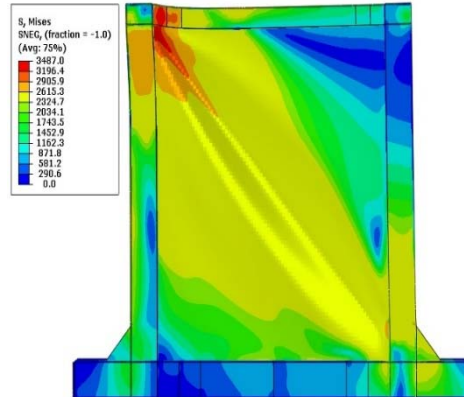
Figure (12): comparing depreciated energy diagrams for the single-story building's frame with flat and corrugated shear walls but in different thicknesses

The statuses of the one-story building's frames used in triangular corrugated and flat shear walls with different thicknesses and 2% of drift (displacement for 7cm above the frame) have been shown in figure (13), according to which the

walls with flat sheets have undergone buckling along their diameters and intense stress occurs at the point of sheet-beam-column connection, and this is in a match with the articles' findings and laboratory tests.

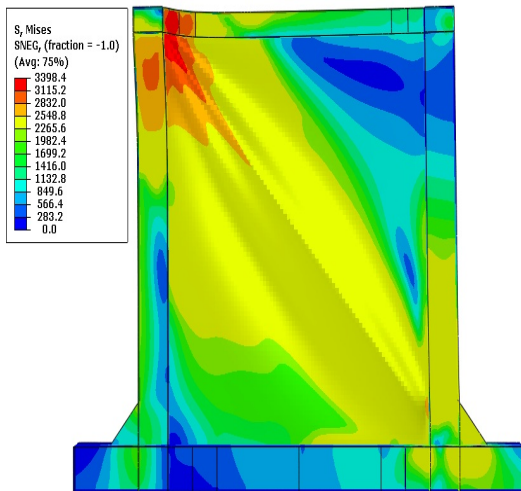


S14

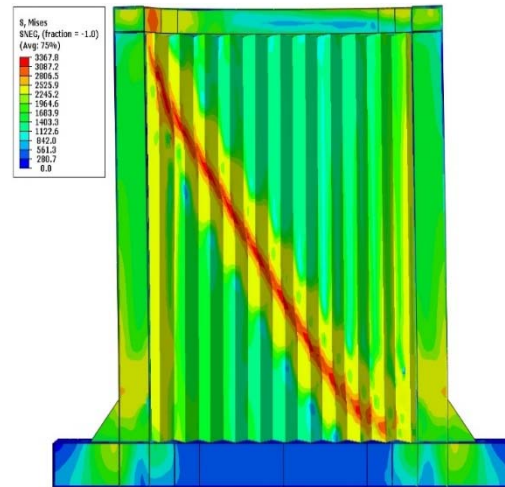


S15

Figure (13): the status of the stress in the one-story building's frames used in triangular corrugated and flat shear walls with various thicknesses and 2% of the drift



S16



TV14

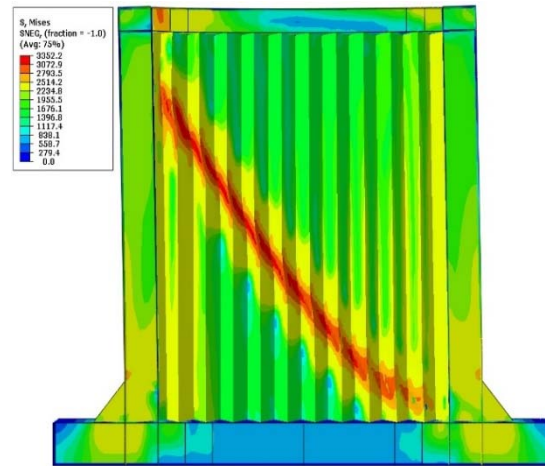
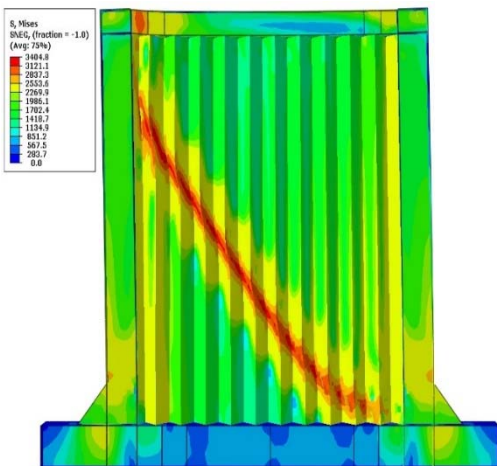


Figure (13) continued: statuses of stresses in the frames used in a one-story building's triangular corrugated and flat shear walls with various thicknesses and drift of 2%

The investigation of the two-story building's triangular and flat shear walls with various thicknesses indicated that the flat shear sheet's buckling and shear force cause a lot of shear deformation in the first story above the column and that the shear deformation is dominant in these frames; however, in the two-story building's shear walls with corrugated sheets, the plastic joints created at the foot of the columns stem from the buckling and cause the frame to undergo deformation along with the sheet's buckling. Thus, in these frames, the shear deformation and buckling occur concomitantly. So, considering the above sayings and the pushover diagrams, the shear walls made of corrugated triangular sheets outperform the shear walls made with flat sheets, and the increase in the thickness of the triangular corrugated sheet helps these walls perform better.

The investigation of the four-story building's shear walls with triangular corrugated and flat sheets with various thicknesses indicated for the four-story building's frames with flat shear walls that the sheets' buckling and deformations stemming from the beams and columns' plastic joints and the buckling of the column about the axis perpendicular to the frame's surface cause nonlinear deformations and that the buckling of the columns accounts for a larger quotient in decline in the frames'

strength rates. The frames with corrugated shear walls undergo lower buckling in their sheets if their thicknesses are increased, and the compressive load-bearing capacity of the columns is increased with the increase in the corrugation rates of the sheets, and this helps their strength to decline lower. Hence, the frames with triangular corrugated shear walls have far better behavior and performance.

The investigation of the eight-story building's shear walls made of triangular corrugated and flat sheets with different thicknesses indicated that the more the thickness of the sheet (triangular corrugated and flat) is increased, the more elastic stiffness of the frame is equally increased. The triangular corrugated sheets have higher elastic stiffness than the flat sheets. The frames made of flat sheets undergo softening after reaching the maximum yield point in such a manner that the diagram's slope for all three thickness rates of the flat sheet would be negative after reaching the maximum negative point, and the strength rates of the frames severely reduce with an approximately similar slope in higher drifts. The sheets with triangular corrugation also continue resisting after experiencing the maximum stress (reaching yield point) and decline their strengths in drifting above 2.5% but with a relatively mild slope.

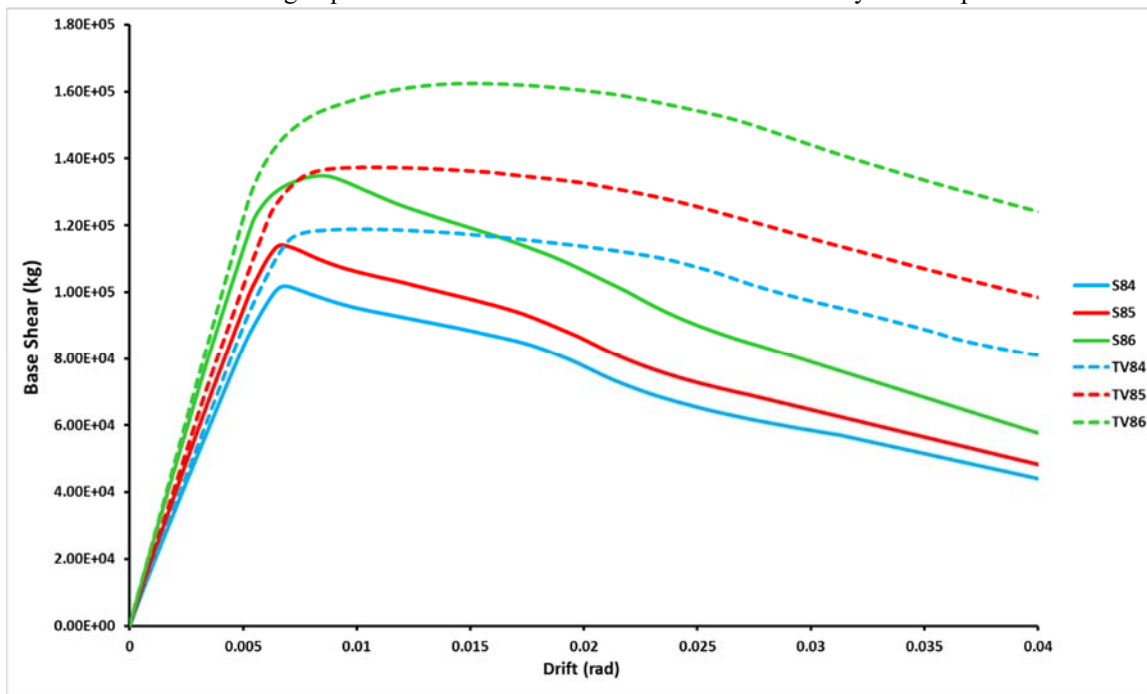


Figure (14): comparing the pushover diagrams of the eight-story frames made of flat and corrugated shear walls with various thicknesses

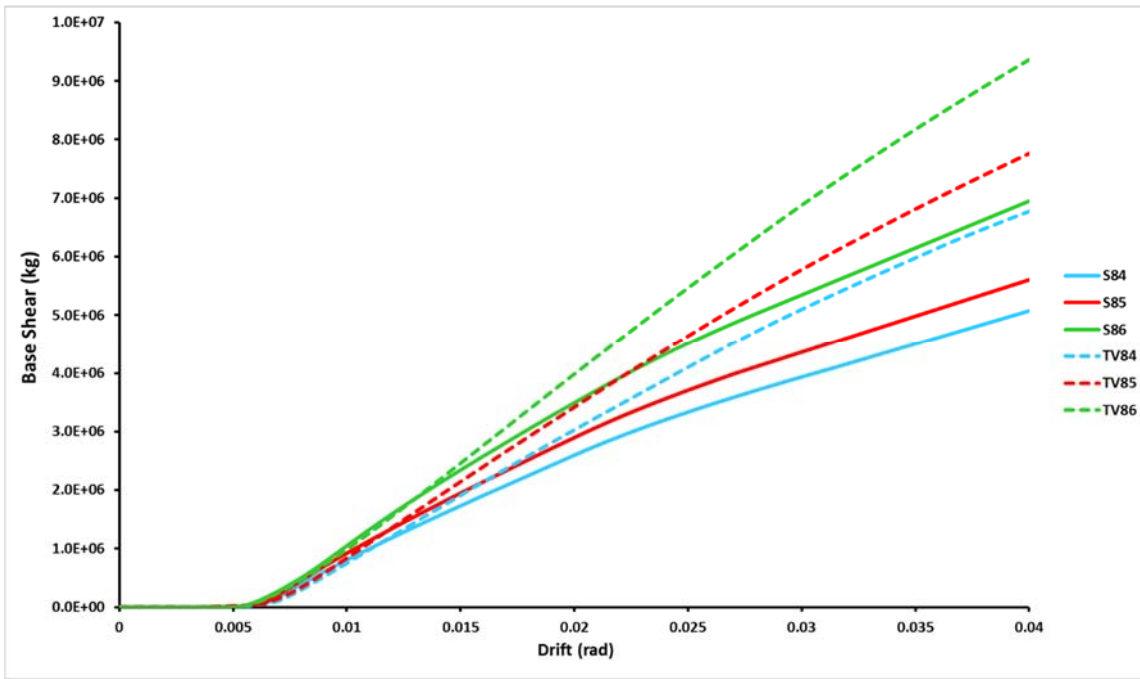


Figure (15): comparing the energy depreciation diagrams of the eight-story building's frames made of flat and corrugated shear walls with different thicknesses

3. Comparing Frames with Triangular Corrugated Shear Walls or with Horizontal and Vertical Corrugation

Figures (16) and (17) show the pushover and depreciated energy diagrams for the 1-, 2-, 4- and 8-story buildings' frames made of vertically and horizontally corrugated shear wall sheets with 4mm thicknesses. According to figure (16), the maximum strength of the frames made of vertically corrugated shear wall sheets is larger than those made of horizontally corrugated shear wall sheets. As for the 1- and 2-story building's frames, vertically corrugated shear wall sheets show better behavior in the beginning, but, after a while and with the increase in the drift, the horizontally corrugated frames can resist the seismic load for a longer period. Regarding the 4- and 8-story buildings' frames, vertically corrugated shear wall sheets exhibit better strength for all of the drift percentages, which can be due to the extra strength created due to the column-like performance of the corrugation close to the column in the shear wall on the first floor. In 4- and 8-story

building frames, the buckling of the columns about the axis parallel to the wall plane causes much decline in strength and large deformation. Therefore, the corrugation near the columns helps the vertically corrugated shear wall sheets bear larger loads and depreciate the compressive force on the columns, as a result of which the columns undergo buckling after a longer period. According to figure (17), energy absorption in the 4- and 8-story building's frames is larger in vertically corrugated shear wall sheets compared to horizontally corrugated shear wall sheets. In contrast, energy dissipation of the horizontally corrugated shear wall sheets is larger in two-story building frames.

The vertically corrugated shear wall sheets exhibit larger elastic stiffness. Considering the better performance of the vertically corrugated shear wall sheets in contrast to horizontally corrugated shear wall sheets, the former is used in this dissertation to compare the various thicknesses of the shear wall sheets.

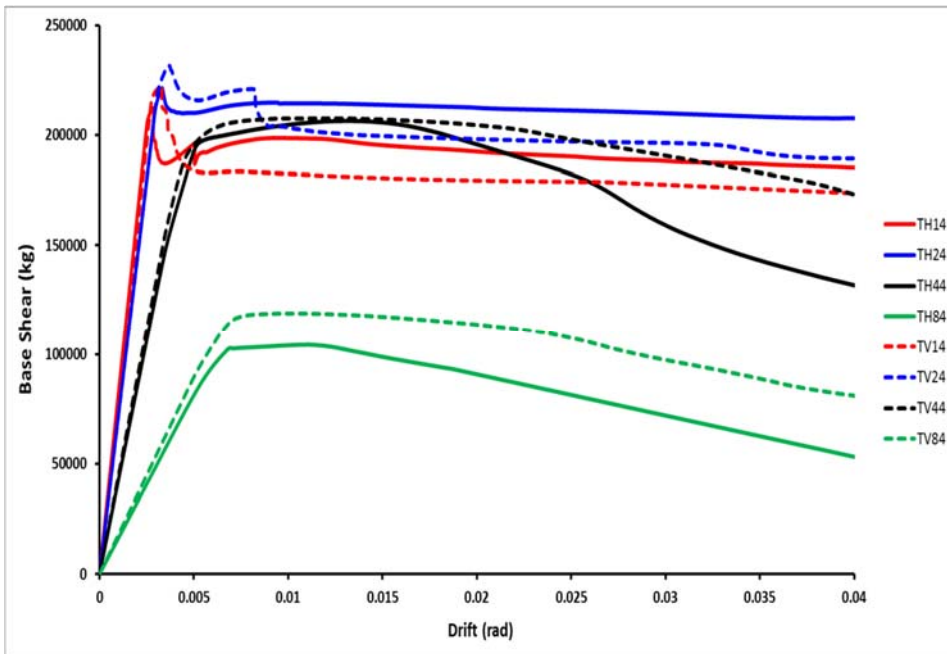


Figure (16): comparison of the pushover diagrams of the 1-, 2-, 4- and 8-story buildings' frames made of triangular vertically and horizontally corrugated shear wall sheets

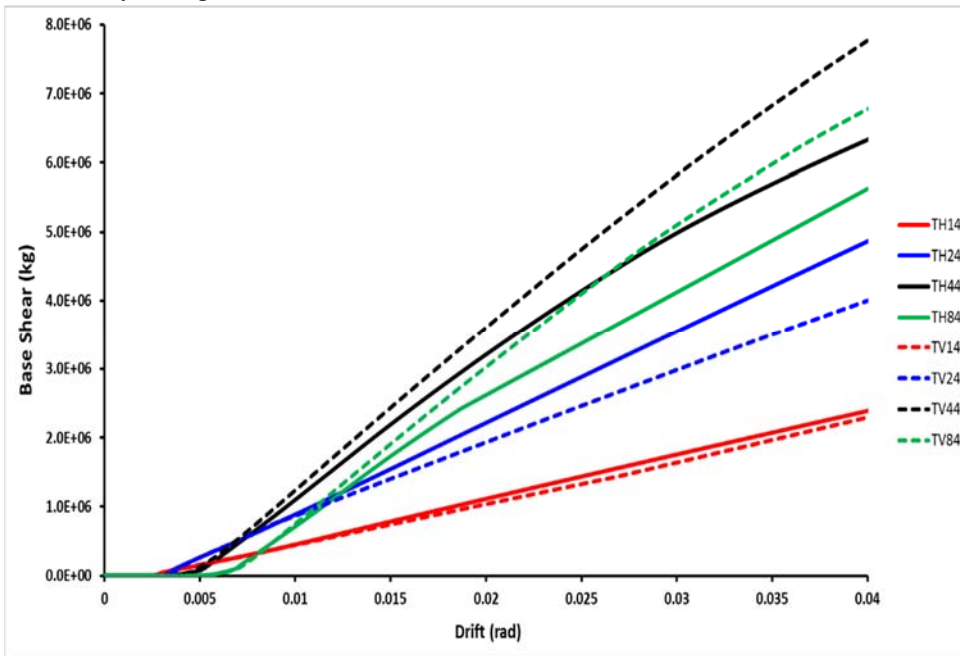


Figure (17): comparison of the energy dissipation diagrams of the 1-, 2-, 4- and 8-story buildings' frames made of triangular vertically and horizontally corrugated shear wall sheets

Conclusion:

To investigate the behaviors of the triangular corrugated sheets in shear wall panels, 16 models with different corrugation lengths and amplitudes were investigated. Using the sheets with corrugation length to corrugation amplitude ratio below 0.5 (the weight of the steel used in contrast to the flat sheet is below 2.3 times) is economically justifiable. However, the amount of the used steel is very high for the other sheets (corrugation amplitude to length ratios above 0.5), so if the

performance of these sheets is not considerably better than the others, their use is not economically justified.

In the frames made of triangular corrugated sheets with a fixed length, the more the corrugation amplitude is increased, the more the initial hardness is reduced, and the more the corrugation amplitude is increased, the more the maximum strength of the shear wall (maximum base shear) is reduced.

In the frames made of triangular corrugated sheets with 5-cm corrugation amplitude and variable corrugation length, the more the latter is reduced, the better the post-buckling behavior

of the sheet in terms of resistance and strength. In the frames with fixed 5-, 10-, 15- and 20-cm corrugation amplitude, the initial stiffness is inversely correlated with the corrugation length. Thus, an increase in the corrugation length causes an increase in the elastic stiffness of the frames made of triangular corrugated shear walls.

In the 1- and 2-story buildings' frames and lower drift percentages (below 1%), the vertical frames behave better but, in continuation and with the increase in the drift, the strength of the horizontally corrugated frames is a little larger than that of the vertically corrugated frames. As for the 4- and 8-story buildings' frames and all of the drift rates, the strength of the frames with vertically corrugated shear wall sheets is larger for such a reason as the extra strength created due to the column-like performance of the corrugation close to the shear wall's column on the first floor.

From a drift rate of 1% up, the flat sheet with a thickness of 4mm exhibits higher strength in contrast to the triangular corrugated sheet. Up to a drift of 4%, the strength of the triangular corrugated sheet is always higher when it is 5mm thick compared to the flat sheet. The triangular sheets with a thickness of 6mm behave a lot better than the flat sheets for all drifts.

As for the 2-story buildings' frames, the behavior of the triangular corrugated shear wall sheets is better, and their maximum strength is larger than that of the flat sheets of the same thickness. The curves of the frames with flat and corrugated sheets and with 4-millimeter thickness and the curves of the 5-milliliter sheets intersect respectively in 1% and 3% drifts. Therefore, the strength of the flat sheets is larger in higher drifts.

Four-storey building frames made of triangular corrugated shear wall sheets can absorb more energy compared to the specimens made of flat sheets for similar 4-mm, 5-mm, and 6-mm thicknesses.

The triangular corrugated sheets in the frames of the 8-story buildings would be much better and more useful than the flat sheets. As one finding, it can be asserted that if the results of the design works end in favor of the flat sheets, triangular corrugated sheets can be utilized even for lower thickness rates for their better seismic performance.

It is suggested that the effects of various length-to-height ratios of the frames' spans and various thicknesses of the triangular corrugated shear wall sheets should be investigated for higher elevations of the buildings.

Acknowledgments

None.

Conflict of interest

None.

Financial support

None.

Ethics statement

None

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