Latin American Journal of Solids and Structures
www.lajss.org

Evaluation and comparison of behavior of corrugated steel plate shear walls

Abstract

In this paper, the nonlinear behaviour of steel plate shear walls with corrugated plates under lateral pushover loading conditions in the models' top level has been analytically investigated by the finite element method. The one-storey frames have beams and columns as boundary elements. Steel plate shear walls are simulated using the finite element method, based on the available experimental models in the literature. After calibration of the analytical models, more parameters of steel shear walls with corrugated plates, such as the thickness of the corrugated plate, the stiffness of the boundary elements, the corrugation depth in the corrugated plates and the corrugation length of the infill of the corrugated plates, are investigated. The results of this study have demonstrated that in the wall with constant dimensions, the trapezoidal plates have higher energy dissipation, ductility and ultimate bearing than sinusoidal waves, while decreasing the steel material consumption.

Keywords

Steel shear wall; sinusoidal corrugated plate; trapezoidal corrugated plate; energy dissipation; ductility; ultimate bearing.

Y.Yadollahi [a]
I. Pakar [b]
M. Bayat [c*]

[a] Department of Civil Engineering, Shomal University, Amol, Iran
[b] Young Researchers and Elite Club, Mashhad Branch, Islamic Azad University, Mashhad, Iran
[c] Department of Civil Engineering, College of Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran

Corresponding author:
*mbayat14@yahoo.com

http://dx.doi.org/10.1590/1679-78251469

Received 20.07.2014
Accepted 21.10.2014
Available online 11.11.2014

1 INTRODUCTION

Steel shear walls have been used in the construction of high-rise structures in most advanced seismic countries, such as the United States, Japan and Canada, for almost three decades. This system has great advantages compared to other similar systems such as reinforced concrete shear wall and steel braces. The benefits of this system include high ultimate bearing, perfect plasticity, high energy absorption capacity, appropriate stiffness, reduced structural weight, lower foundation construction costs, better quality and high-speed construction. The overall structures of steel shear walls consist of boundary elements such as beams and columns, with infill steel plates in the spaces between them. Steel shear walls can be constructed in two types: unstiffened and stiffened. In unstiffened walls, a series of flat plates with light thickness is used for utilizing the post-buckling field under overall buckling. In the second type of wall, a belt series or steel profiles are utilized as stiffeners with different arrangements – horizontal, vertical and diagonal – on one side or both sides of the wall until the energy dissipation, stiffness and ultimate bearing are increased. The first method is completely uneconomical because to improve the hysteresis curve of the walls described it is necessary to increase the thickness of the steel plate until the plate does not buckle before yielding; this increase in thickness will be very significant and uneconomical. The second method, which involves strengthening the plate by a series of stiffeners, is economical and quite effective. By using this method, the hysteresis curves turn from an S-shape to a spindle shape and increase the hysteresis curve area. However, this method, primarily due to welding operations, causes weaknesses of the plate within. It also has higher costs for joining the stiffeners to the wall. (Astaneh-Asl, 2001; Behbahanifard, 2003; Berman et al., 2003).

Corrugated steel plates, due to their ductility and low cost, are an appropriate alternative system in these walls. On the other hand, in corrugate plates, the plate's wave function is similar to that of the stiffeners and it has appropriate stiffness too. The performance of steel shear walls is similar to that of the plate girder; as shown in Figure 1, the plates, columns and beams are the same as its webs, flanges and stiffeners, respectively. (Breman et al., 2005; Driver, 1998; Sabouri-Ghomi et al., 2008).

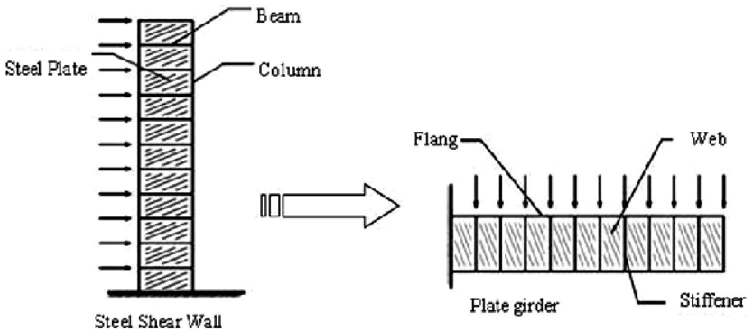

Figure 1: Steel plate shear wall and plate girder analogy.

Investigations into stiffened and unstiffened steel shear walls and more experimental and theoretical works have been carried out by many researchers. Some researchers that have studied in this field are (Breman, 2001; Bruneau, 2002; Formisano et al., 2006; De Matteis et al., 2008; Bhowmick et al., 2011; Chen et al., 2011; Choi et al., 2010; Claytonet et al., 2011).

The investigations of steel shear walls with corrugated plates are limited and more activities in this field have been done on the plate girder system. In the plate girder system, the plates are used vertically in a web. The investigations of plate girders with corrugated steel plates as a web are limited to the laboratory activities of (Elgaaly et al., 1996, 1997; Usman, 2001; Wang, 2003; Gentilinia et al., 2008; Kovesdi, 2010; Tanaka et al., 2008; Sause et al., 2008). Laboratory research on the steel frame with the corrugated plate is limited to the work of (Chosa, 2006; Stojadinovic et al., 2007), who have studied the experimental and numerical aspects of the shear steel panels with corrugated trapezoid-shaped plates under cyclic and uniform loads.

All of the above researches on steel shear walls with corrugated plates have been experimental and have examined only the overall behaviour of the walls under uniformly and cyclic lateral loading, indicating in the end the advantages of this system. According to experimental activities and the outcomes of these types of studies, the investigation has been limited to negligible components of these systems, neglecting different aspects of the corrugated plate, such as the effect of plate thickness on the walls, the effect of the height and length of the plate's wave, the effect of the boundary elements and the effect of openings in the wall and other parameters on the behaviour of these walls. Hence, in this paper these parameters have been studied.

2 FAILURE MODES OF CORRUGATED PLATES

Primarily, the infill plates provide the shear capacity of the frame. The control of the structure's shear strength by the steel plates comes through buckling of the plate or through it failure. Pure shear stress is the only significant stress in these structural components. In corrugated plates, the yield shear stress can be determined with eq. (1) (Sayed-Ahmed, 2005, 2007; Kiymaz et al., 2010)

$$\tau_y = \frac{F_y}{\sqrt{3}} \tag{1}$$

where F_y is the yielding strength of steel.

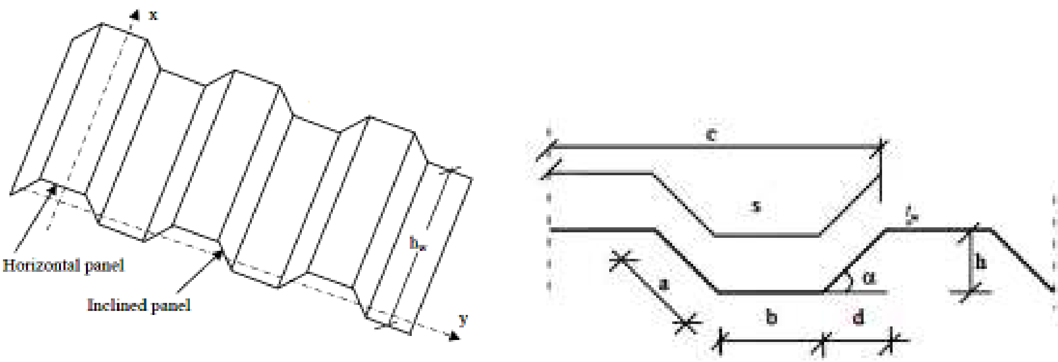

Figure 2: Geometric properties of trapezoidal corrugated plate.

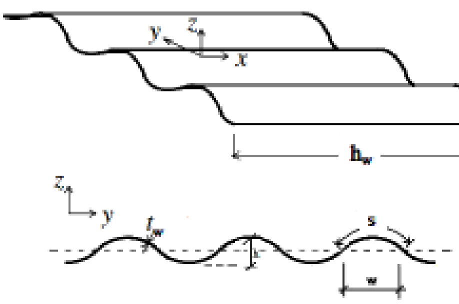

Figure 3: Geometric properties of sinusoidal corrugated plate.

Buckling control of corrugated plates is performed by overall and local buckling. The local buckling mode of the corrugated plates is formed in flat panels of the trapezoidal corrugated plates, primarily, and along the horizontal edge, as shown in Figure 4. In this span, corrugated plates are connected to the short edges of column flange. In these conditions, the local buckling is studied in isotropic plates and the elastic critical shear stress for the local buckling mode is defined by eq. (2) for trapezoidal and sinusoidal plates (Sayed-Ahmed, 2001, 2007; Kiymaz et al., 2010):

$$\text{Trapezoidal} \qquad \tau_{cr,l} = k_s \frac{\pi^2 . E}{12\left(1-\nu^2\right)} . \left(\frac{t_w}{b}\right)^2 \tag{2}$$

$$\text{Sinusoidal} \qquad \tau_{cr,l} = k_s \frac{\pi^2 . E}{12\left(1-\nu^2\right)} . \frac{2t_w}{s} \tag{3}$$

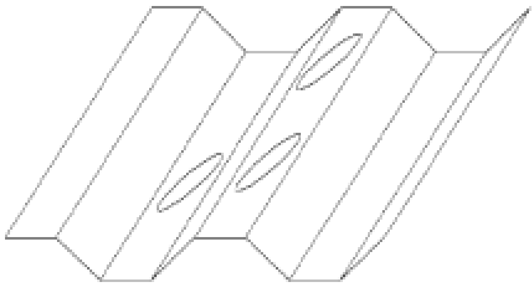

Figure 4: The local buckling form in corrugates of plate.

where t_w is the corrugated plates' thickness, b is length of wave in the trapezoidal corrugated plate in which the local buckling occurs, s is the actual length of the corrugate in the plate with a sinusoidal corrugated plate, E is the modulus of elasticity, ν is the Poisson ratio of steel and k_s is the shear buckling coefficient in the local buckling mode, the value of which is dependent on boundary conditions and the panel's aspect ratio (b/h_w), such that h_w is the height of the plate. This coefficient for trapezoidal corrugated plates is defined by eqs. (4) (Galambos, 1998; Sayed-Ahmed, 2005).

$$k_s = 5.34 + 4.0\left(\frac{b}{h_w}\right) \tag{4.a}$$

$$k_s = 5.34 + 2.31\left(\frac{b}{h_w}\right) - 3.44\left(\frac{b}{h_w}\right)^2 + 8.39\left(\frac{b}{h_w}\right)^3 \tag{4.b}$$

$$k_s = 8.98 + 5.60\left(\frac{b}{h_w}\right)^2 \tag{4.c}$$

Equation (4a) is used when the plate boundary conditions are simple, such as for corrugated plates that are in the web of the plate girder, while equation (4b) is used for the longer edges that are simply supported with the shorted edges clamped; equation (4c) is used when all edges are clamped. The sample of clamped boundary conditions on the short edge of the plate's corrugate is used in the composite beam, with a web of corrugated plates and concrete flanges. This system is usually used in bridge construction.

In eqs. (2), if the inclined width of the corrugated plate a is larger than the horizontal panel width of the inside trapezoidal plate b, it should be considered as the critical width, in which case the inclined width of the plate is the critical zone of its local buckling mode,

$$\text{Sinusoidal} \qquad k_s = 5.34 + \frac{s\,h}{2h_w\,t_w} \tag{5}$$

where h is the height of sinusoidal waves.

According to the stated conditions, if $\tau_l \geq 0.8\tau_y$ then inelastic local buckling will occur on the plate; therefore, inelastic buckling stress is defined by (Galambos 1998):

$$\tau_{l,i} = \sqrt{0.8\tau_l\tau_y} \tag{6}$$

In the equation above, τ_l is shear stress due to local buckling and $\tau_{l,i}$ is shear stress due to inelastic local buckling on the corrugated plate.

According to Figure 5, the global buckling is formed with global diagonal buckling of the multi-waves in the corrugated plate. In this case, the critical shear stress is estimated with respect to the corrugated plate as an orthotropic plate. The critical shear stress of this mode is defined by (Sayed-Ahmed, 2005, 2007; Kiymaz et al., 2010):

$$\text{Trapezoidal} \qquad \tau_{cr,g} = k_g \frac{(D_y\,D_x{}^3)^{1/4}}{h_w^2\;t_w} \tag{7}$$

$$\text{Sinusoidal} \qquad \tau_{cr,g} = k_g \frac{\left(D_x\,D_y{}^3\right)^{1/4}}{h_w^2\,t_w} \tag{8}$$

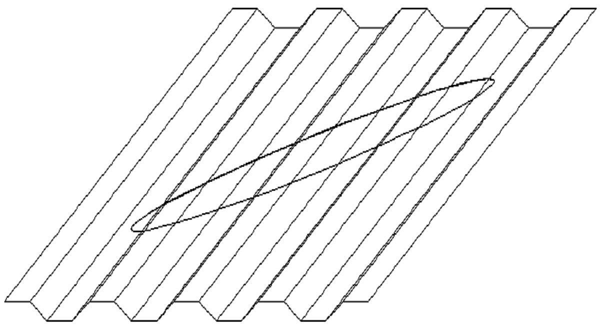

Figure 5: Global buckling on trapezoidal corrugated plate.

where k_g is the global buckling coefficient, which is a function of the panel aspect ratio and the boundary conditions. In a trapezoidal corrugated plate, it is 36 when the longer edges are simply supported and the shorted edges are clamped, such as in the web plate on a plate girder. It is 68.4 for plates where all the edges are clamped, such as in the web plate on a composite beam. In a sinusoidal corrugated plate, k_g is 32.4 for simply supported and 60.4 for clamped boundary conditions. The factors D_x and D_y are plate rigidities in the longitudinal, x, and traverse, y, direction that are given as:

Trapezoidal
$$D_y = \frac{E\,t_w^3}{12\left(1-\nu^2\right)} \cdot \frac{b+d}{b+a} \tag{9}$$

$$D_x = \frac{Et_w h^2}{12} \cdot \frac{3b+a}{b+d} \tag{10}$$

Sinusoidal
$$D_y = \frac{Et_w^{\;3}}{12\left(1-\nu^2\right)} \cdot \frac{w}{s} \tag{11}$$

$$D_x = \frac{EI_x}{w} \tag{12}$$

where a is the inclined panel width in the trapezoidal plate, d is the horizontal projection of the inclined panel width, w is the horizontal projection of the one wave on the sinusoidal plate and I_y is the second moment of the area of one wave length of the web, which has a projected length as defined by (Szilard et al., 2004):

$$I_y = \frac{h^2 t_w}{8}\left[1 - \frac{0.81}{1+2.5\left(h/4w\right)^2}\right] \tag{13}$$

If $\tau_g \geq 0.8\tau_y$, then inelastic buckling will happen on the plate and the inelastic critical shear stress for the global buckling mode will be as given by (Galambos, 1998).

$$\tau_{l,g} = \sqrt{0.8\tau_g\tau_y} \tag{14}$$

In the equation above, τ_g is shear stress due to global buckling and $\tau_{g,i}$ is shear stress due to inelastic global buckling in the corrugated plate.

Elgaaly (1996) in his laboratory research on the trapezoidal corrugated plates has shown that if the waves of the corrugated plate are large then the local buckling can form in the horizontal portion of each corrugated plate; however, if the lengths of waves are small then the global buckling can form in the plate without control.

However, these equations above were used on a plate girder with trapezoidal and sinusoidal waves. Therefore, this paper refers to the comparison of results obtained by the finite element method.

3 MODELING AND THE VALIDATION OF SIMULATION

This section outlines the application of the assumptions used for modelling and evaluates the method that selected the validation of the simulation by software modelling.

3.1 Numerical Modeling and analyses of steel shear wall

The numerical analyses were performed on one-storey and one-span wall of 3000 mm width and 2600 mm height. The boundary element was IPB180 for columns and IPE180 for beams. The infill plate used in this wall was a sinusoidal and trapezoidal corrugated plate, rigidly connected to the surrounding frame.

The ANSYS finite element package (Ansys, Ver 10) and arc-length method was used to solve the numerical models. The size of element meshing and time stepping were considered to be 50 mm and 0.001 to ensure good accuracy and convergent. Using the output variable identifiers as outlined in ANSYS, output data were requested for the generation of load-displacement curves. Boundary elements and infill walls are finely meshed and modeled by the four-node shell element 143.

SHELL143 is well suited to model nonlinear, flat or warped, thin to moderately-thick shell structures. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. The deformation shapes are linear in both in-plane directions. For the out-of-plane motion, it uses a mixed interpolation of tensorial components (Ansys, Ver 10). The geometry, node locations, and the coordinate system for this element are shown in Figure 6. The element is defined by four nodes, four thicknesses, and the orthotropic material properties. The element has plasticity, creep, stress stiffening, large deflection, and small strain capabilities. This shell is particularly useful for modeling sheet metal or thin structural parts.

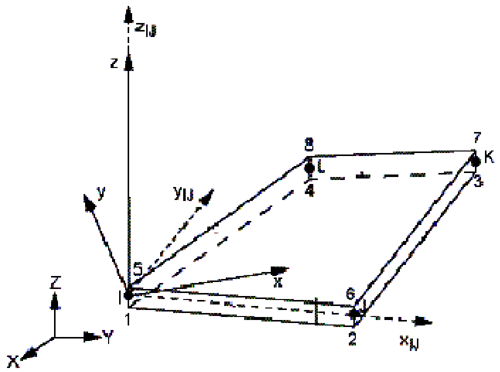

Figure 6: SHELL143 Geometry.

Shell models used for simplify 3-D models to a set of different part of models including boundary elements and infill plate with a defined thickness and shell parts meshed with quad-dominant meshes. The geometry and meshing configurations of these walls are shown in Figure 7. The walls were supported by clamps on the bottom of the wall. Simple supports in the out-of-plane direction were given for prevention of out-of-plane displacement all around the frame.

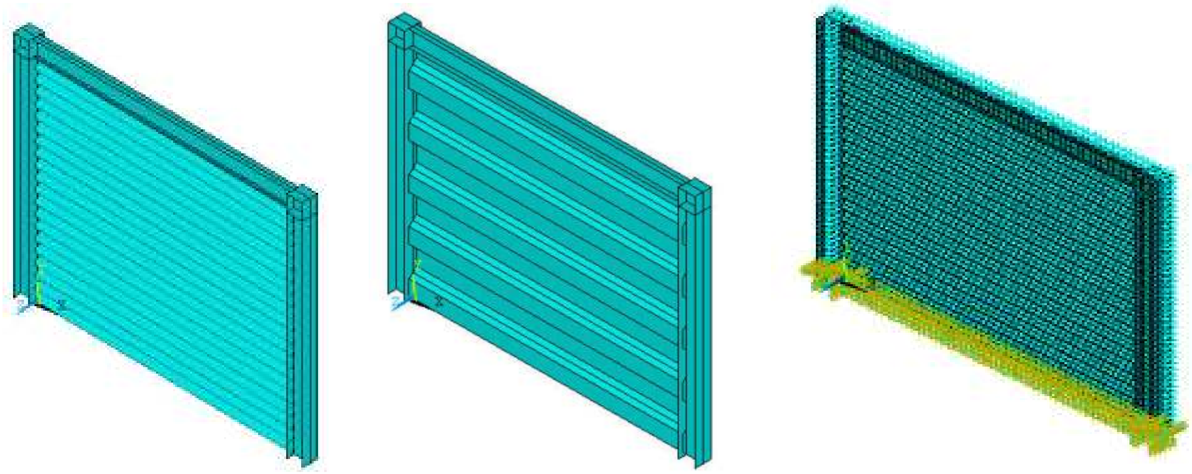

Figure 7: The schematic corrugated steel shear wall with a) sinusoidal and b) trapezoidal waves c) finite element model.

In order to study the nonlinear behaviors of infill walls and frame members, stress_strain diagrams that define the constitutive behaviors of the steel materials is shown in Figure 8. In these models, an elastic-plastic material model was assumed with a yield strength value of 240 MPa, a modulus of elasticity $E = 200$ GPa, a Poisson ratio $\nu = 0.3$ and a tangent modulus of 3 % of the modulus of elasticity. The geometric nonlinearity phenomenon is included as a consequence of large displacements with small strains. In reality, the thin infill plates upon mounting are already in a buckled shape due to fabrication process, welding distortion and assemblage.

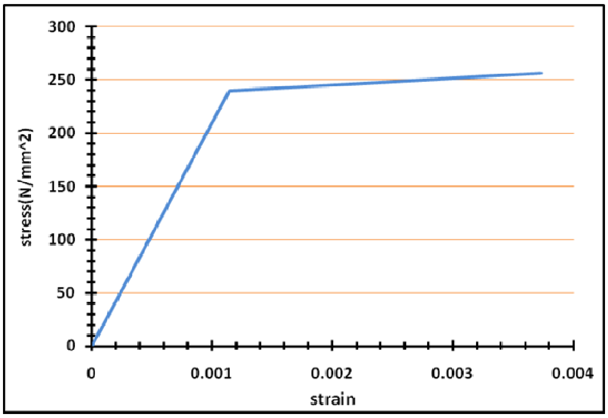

Figure 8: Material stress_strain curves.

3.2 Assumptions and the validation of modeling

For validation of the accuracy assumptions in the simulation and determining their accuracy, the experimental results should be compared with the results obtained by the ANSYS finite element software. Given the unavailability of full experimental results for all the characteristics of corrugated steel shear walls, the experimental activities of Usman (2001) on plate girders were taken as the first models of TS600-3. In this study, plate girders with a trapezoidal web plate were investigated under monotonic loading. The geometric properties of the plate girder as determined by the software are shown in Figure 9 and table 1.

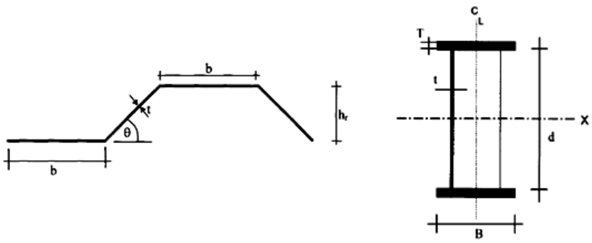

Figure 9: Geometric properties of TS600-3 specimen (Usman, 2001).

θ	B	T	D	h_r	t	b
45	200	15	600	80	3	170

Table 1: Dimensions of TS600-3 plate girder (mm).

The steel material consumed has an elastic-plastic curve of strain-stress with a modulus of elasticity 200 GPa. The Poisson ratio is 0.3 and the yield strength is 355 MPa. The Von Mises criteria are used for evaluation of the mode result because steel material was applied. The force and displacement criteria are the convergent criteria. The element SHELL143 is used for the flange, web and stiffener in experimental plate girder modelling using ANSYS software. The experimental activities were performed on three plate girders which were designed as a one-span beam with simple supports, onto which the monotonic load was applied at the first (A), middle (B) and end (C) thirds of the beam span. According to Figures 10, 11 and 12, the results of numerical analysis with ANSYS are acceptable with respect to experimental models. These results demonstrated the validity of the simulation for element type, size meshing and assumption of problem. The minor differences in results are due to the type of study tools.

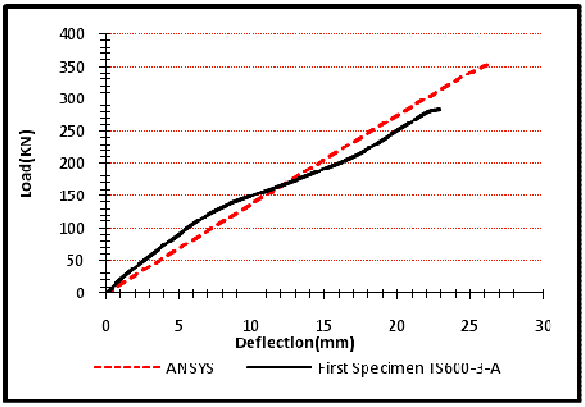

Figure 10: Load – displacement curve of experimental and ANSYS model (A).

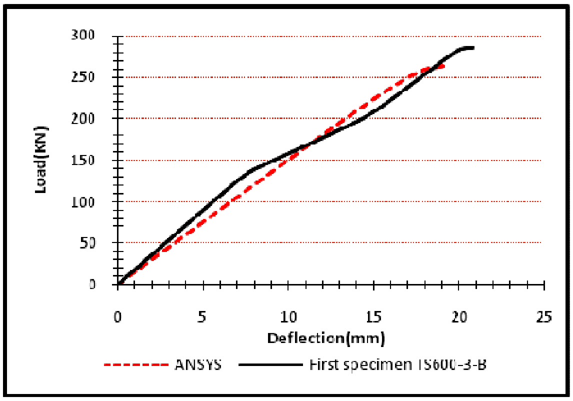

Figure 11: Load – displacement curve of experimental and ANSYS model (B).

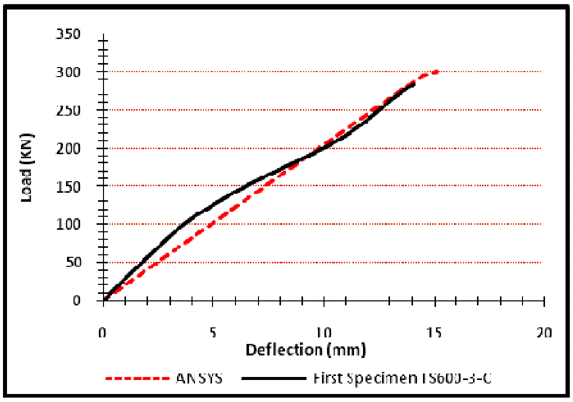

Figure 12: Load – displacement curve of experimental and ANSYS model (C).

4 EVALUATION OF THE PARAMETRIC STUDY RESULTS

In this part, the results of the effects of some geometric properties, such as thickness of plate, depth or wave height of plate, length of wave, corrugated density and stiffness of beam and column, on corrugated steel walls were investigated. The results of these parameters are presented in detail.

4.1 The thickness effect of the corrugated plate

The thicknesses that are considered for the study of the effect of thickness on sinusoidal and trapezoidal corrugated plate are 1.5, 3, 5, 10, 15 and 20 mm. In these models, the columns and beams were considered to be IPB180 and IPE 180. The geometric properties of the applied plates are demonstrated in Figures 2 and 3 and tables 2 and 3. In these tables, w is the horizontal projection of the single wave on the sinusoidal plate, b is the horizontal panel width in the trapezoidal plate, h is the corrugation magnitude, t_w is the plate thickness, s is the unfolded length of one corrugation in the sinusoidal plate, a is the inclined panel width in trapezoidal plate, d is the horizontal projection of the inclined panel width, c is the horizontal projection of one wave on the trapezoidal plate, α is the corrugation angle in the trapezoidal plate and $h/2w$ and h/c coefficients are the corrugation density in the corrugated plates.

$h/2w$	H	W
0.16	19	60

Table 2: Geometrical dimensions of sinusoidal plate.

h/c	α	d	A	h	B
0.16	45	80	113	80	170

Table 3: Geometrical dimensions of trapezoidal plate.

According to the results shown in Figures 13 and 14 for sinusoidal and Figures 15 and 16 for trapezoidal corrugated plates with six different thicknesses, the ultimate bearing capacity and energy dissipation are increased with increasing the thickness. Also, in these walls, out-of-plane deformation of the wall progresses to a plastic hinge formation in nearly all beam-to-column connections when the plate thickness increases. It is necessary to explain that the results of the increase of thickness on ultimate bearing were predictable and demonstrate the accuracy of the software's performance.

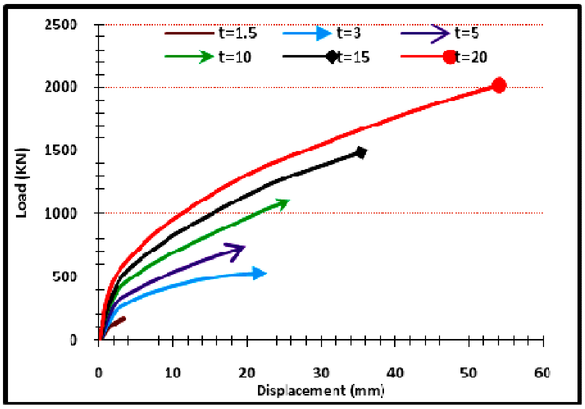

Figure 13: Load- displacement curves of sinusoidal corrugated plates with different thickness.

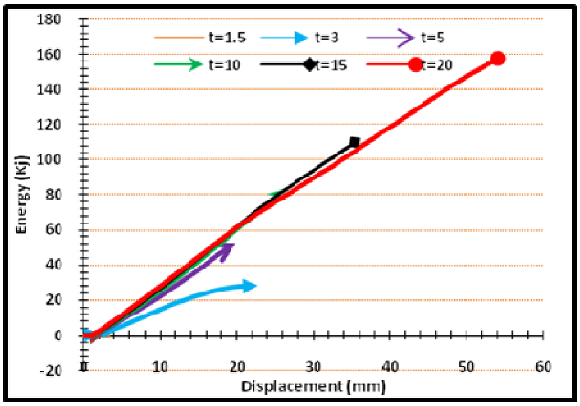

Figure 14: Energy- displacement curves of sinusoidal corrugated plates with different thickness.

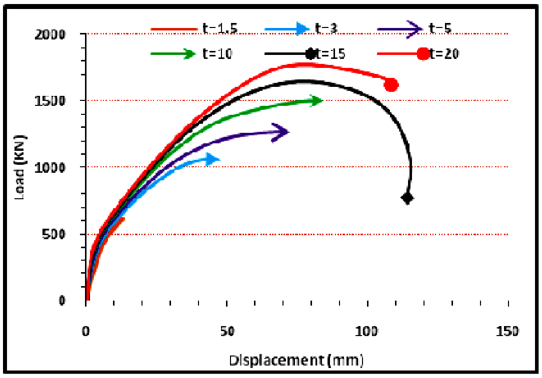

Figure 15: Load- displacement curves of trapezoidal corrugated plates with different thickness.

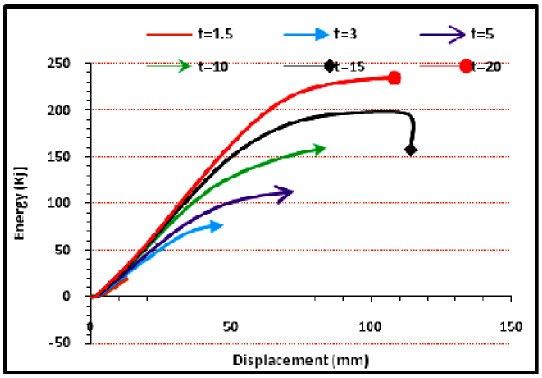

Figure 16: Energy- displacement curves of trapezoidal corrugated plates with different thickness.

With compression, the load-displacement and energy-displacement curves in sinusoidal and trapezoidal steel corrugated plates, assuming that corrugation density is equal to 0.16 for both plates, show that corrugated plate with a trapezoidal wave has more ductility than that with a sinusoidal wave. According to the results, it therefore has higher energy dissipation. In both walls, if the plate has less thickness, then the trapezoidal plate has better performance in ultimate bearing and energy dissipation, but with high thickness of plate, the sinusoidal plate has more ultimate bearing. The sinusoidal plates yield under buckling and the trapezoidal plates yield under the plastic hinge formation on the beam.

The stiffness performance of the one-storey steel shear wall system with sinusoidal and trapezoidal corrugated plate under in-plane load is shown in Figures 17 and 18. These diagrams show that with increases in the plate's thickness, stiffness is increased in the elastic and post-elastic range. Also, the stiffness of all models is gradually decreased without any abrupt change, even at the onset of shear buckling. As shown in Figures 17 and 18, with increased plate thickness, the sinusoidal corrugation plate has more stiffness than the trapezoidal corrugated plates. Also, the stiffness drop slope is greater in trapezoidal plates.

4.2 The stiffness effect of the boundary members

To study the boundary elements, such as beams and columns, in corrugated steel shear wall, six different sections of IPB are used for columns in a sinusoidal corrugated plate, in which the length of wave is 60 mm, the height of wave is 19 mm and the thickness of plate is 3 mm. The columns studied in this section consist of IPB200, 220, 240, 260 and 300, and unique sections of IPE180 are used for beams in these six models. In these models, an increase in the section area of the column leads to an increase in the ultimate bearing due to increased stiffness, according to Figures 19 and 20. But the energy dissipation has no specific process.

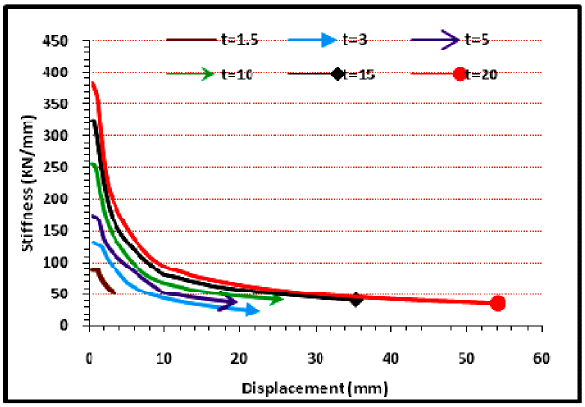

Figure 17: Performance of stiffness in sinusoidal corrugated plates with different thickness.

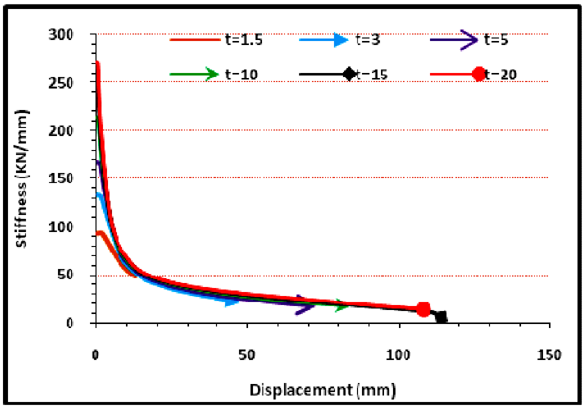

Figure 18: Performance of stiffness in trapezoidal corrugated plates with different thickness.

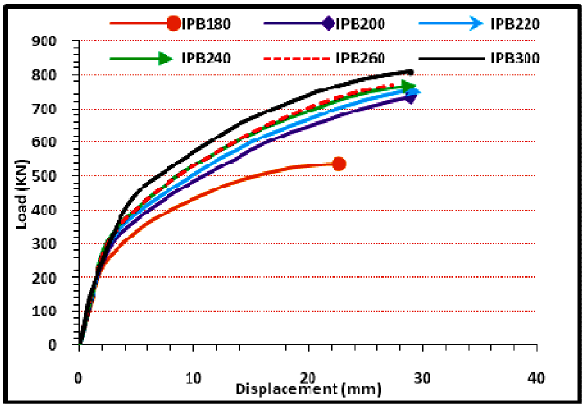

Figure 19: Load- displacement curves of sinusoidal corrugated plates with different columns.

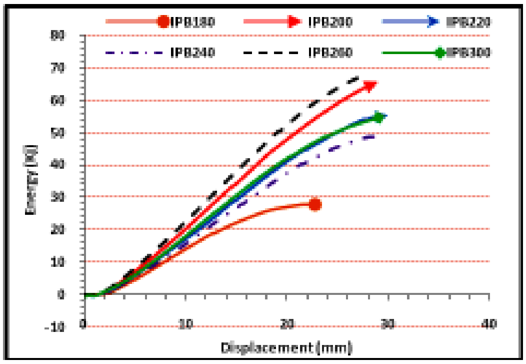

Figure 20: Energy- displacement curves of sinusoidal corrugated plates with different columns.

The stiffness performance with different columns is shown in Figure 21. As outlined, with increases in the column section area, the stiffness of the system has increased about three times to 15.6 %.

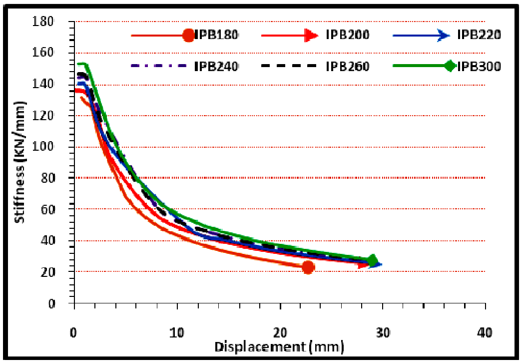

Figure 21: Performance of stiffness curves sinusoidal corrugated plates with different columns.

The beam sections that are studied in this paper are IPE180, 200, 220, 240, 270 and 300 and the column section is IPB180. According to Figures 22 and 23, by increasing the beam section it is shown that the ultimate bearing and stiffness of frame are increased, but the energy dissipation has no reasonable process but can be tell that energy dissipation process is increasing approximately.

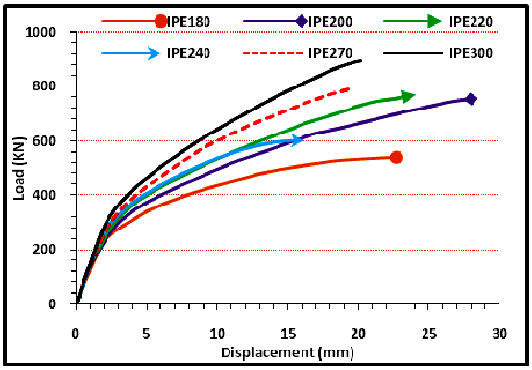

Figure 22: Load- displacement curves of sinusoidal corrugated plates with different beams.

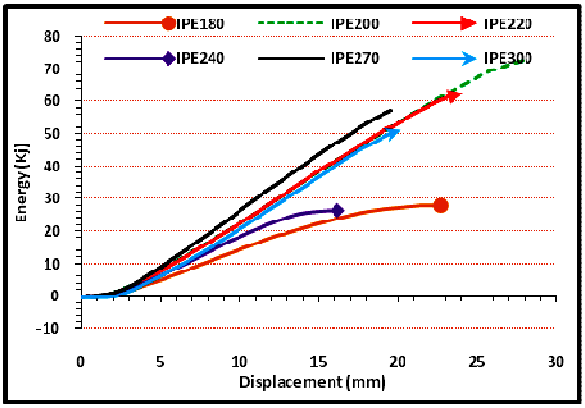

Figure 23: Energy- displacement curves of sinusoidal corrugated plates with different beams.

The stiffness performance of one-storey steel shear wall with sinusoidal corrugated plates is shown in Figure 24. According to this figure, the stiffness is increased about three times to 14.3 % with increase in the beam section. In addition, the stiffness of the system underwent a decreasing process without drop change during the loading.

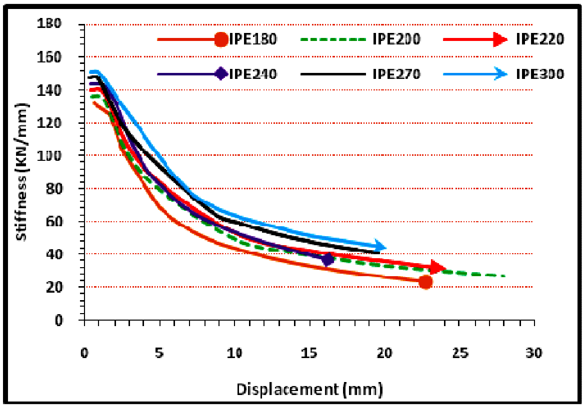

Figure 24: Performance of stiffness curves sinusoidal corrugated plates with different beams.

4.3 Corrugation depth effect in corrugated plates

The corrugation depth is one of the parameters that increased the lateral stiffness of the corrugated plates. In this part, the effect of corrugation depth is studied on steel shear wall behaviour with sinusoidal and trapezoidal corrugation. To study the effect of corrugation depth on sinusoidal corrugated plates, six specimens with different height of 19, 30, 40, 50, 56 and 60 mm are used. The geometric characteristics of these plates are shown in table 4.

H	t_w	w
19, 30, 40, 50, 56, 60	3	60

Table 4: Geometrical characteristic of sinusoidal plates with different corrugation depth (mm).

The results of these specimens under in-plane loading are shown in Figures 25 and 26. These results demonstrate that with an increase in the corrugation depth, the ultimate bearing in the sinusoidal plate increased significantly. In addition, the energy dissipation shows an increasing trend. The results show that ductility is increased with increasing corrugation depth. The key point demonstrated in Figure 27 is the 4.2 % to 17.6 % decrease in stiffness with increasing corrugation depth. According to this figure, the stiffness decrease is a result of increased ductility.

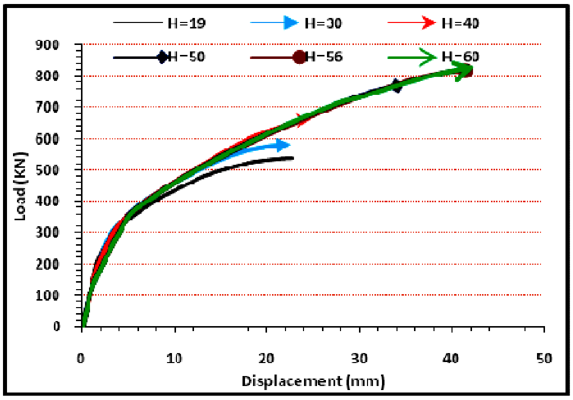

Figure 25: Load- displacement curves of sinusoidal corrugated plates with different corrugation depth.

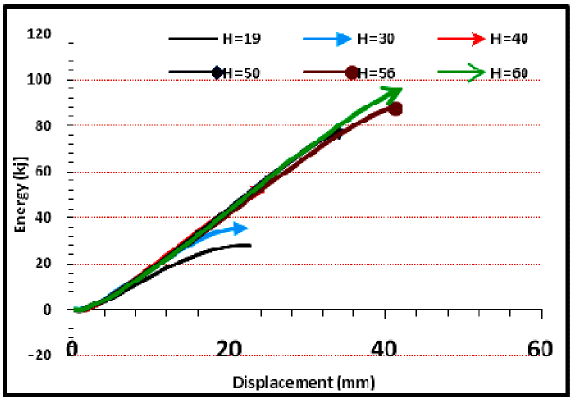

Figure 26: Energy- displacement curves of sinusoidal corrugated plates with different corrugation depth.

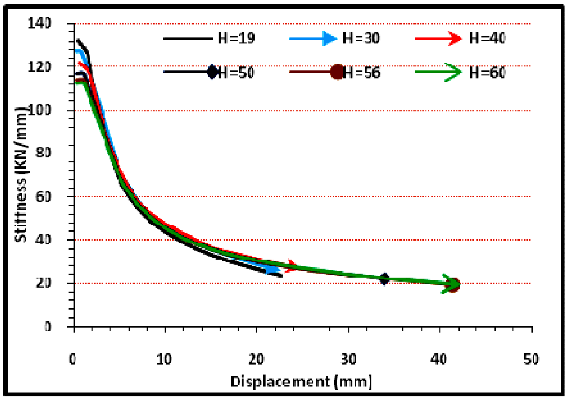

Figure 27: Performance of stiffness curves sinusoidal corrugated plates with different corrugation depth.

The effect of corrugation density on the behaviour of this system in terms of ductility, ultimate bearing and energy dissipation can also be measured. Figures 28, 29 and 30 show that the ductility, energy dissipation and ultimate bearing increase with increases in the corrugation depth or corrugation density coefficient.

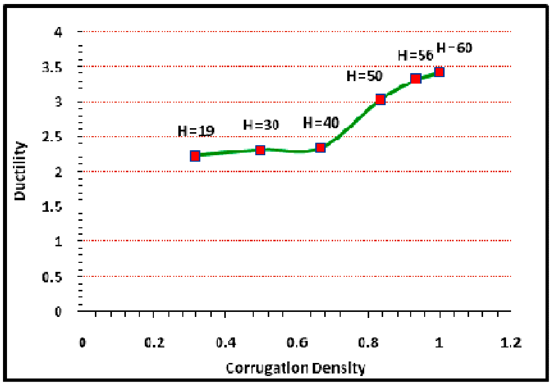

Figure 28: Corrugation Density effect of sinusoidal corrugated plate on ductility.

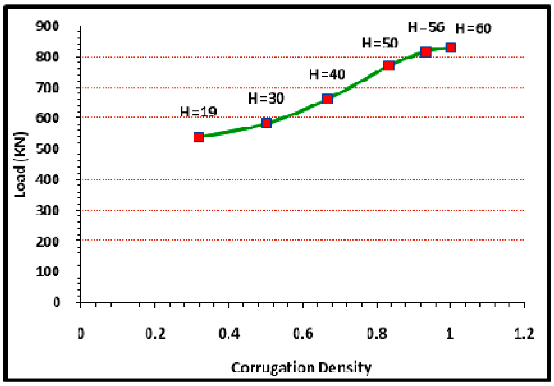

Figure 29: Corrugation Density effect of sinusoidal corrugated plate on ultimate bearing.

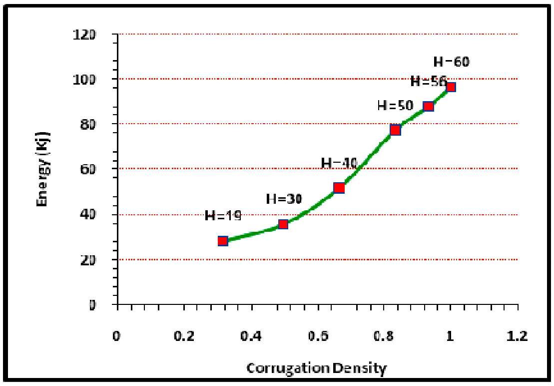

Figure 30: Corrugation Density effect of sinusoidal corrugated plate on energy dissipation.

To study the effect of the corrugation depth in trapezoidal corrugated plates, five specimens and their characteristics are demonstrated in table 5.

d	a	t_w	h	b
40, 50, 60, 70, 80	113	3	80	170

Table 5: Geometrical characteristic of trapezoidal plates with different corrugation depth (mm).

According to the results in Figures 31 and 32, increases in corrugated height have insignificant effects on ultimate bearing, energy dissipation and ductility. The stiffness of wall is uniform; its approximate performance is shown in Figure 33.

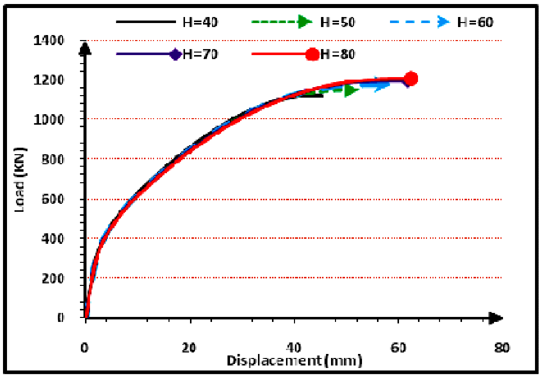

Figure 31: Load- displacement curves of trapezoidal corrugated plates with different corrugation depth.

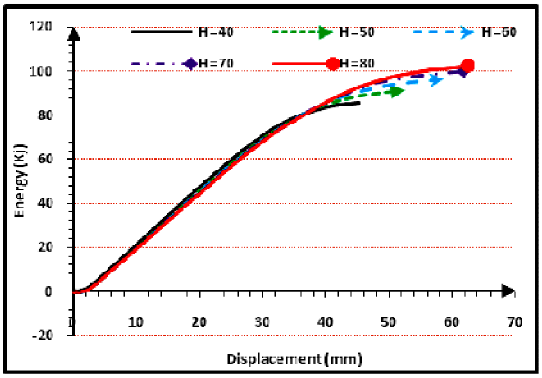

Figure 32: Energy- displacement curves of trapezoidal corrugated plates with different corrugation depth.

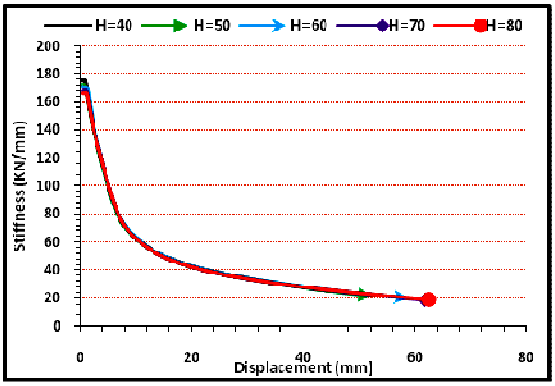

Figure 33: Performance of stiffness curves trapezoidal corrugated plates with different corrugation depth.

4.4 The Corrugation length effect of infill corrugated plates

In this part, seven specimens of sinusoidal and four specimens of trapezoidal corrugated plate were used for studying corrugation length. The geometric characteristics of these models are shown in table 6 and 7, where L is the corrugation length equal to w in sinusoidal plates and equal to $d+b$ in trapezoidal corrugated plates.

h	t_w	$L=1$
19	3	60, 8, 100, 120, 140, 160, 180

Table 6: Geometrical characteristic of sinusoidal plates with different corrugation length (mm).

h	t_w	L
80	3	130, 180, 250, 280

Table 7: Geometrical characteristic of trapezoidal plates with different corrugation length (mm).

Figures 34, 35 and 36 show that for sinusoidal corrugated plates the ultimate bearing and energy dissipation of the wall decreased with increases in the corrugation length and the walls lost bearing due to global buckling failure. The stiffness performance of sinusoidal corrugated plate shows that the initial stiffness did not change with increased corrugation length, but the ductility of wall changed considerably.

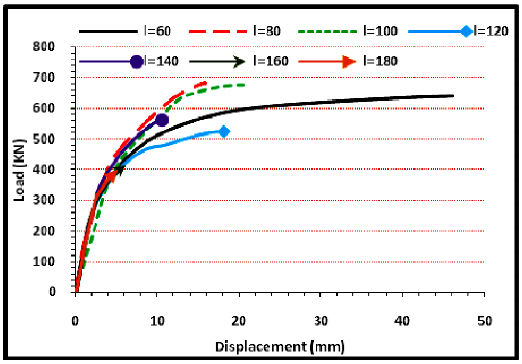

Figure 34: Load- displacement curves of sinusoidal corrugated plates with different corrugation length.

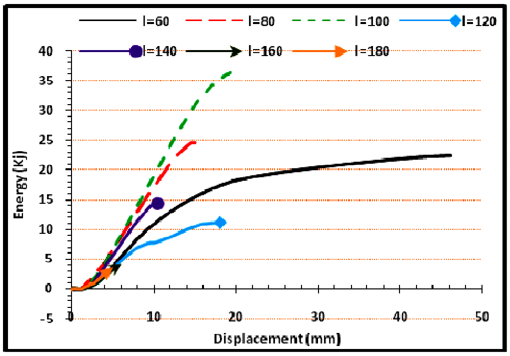

Figure 35: Energy- displacement curves of sinusoidal corrugated plates with different corrugation length.

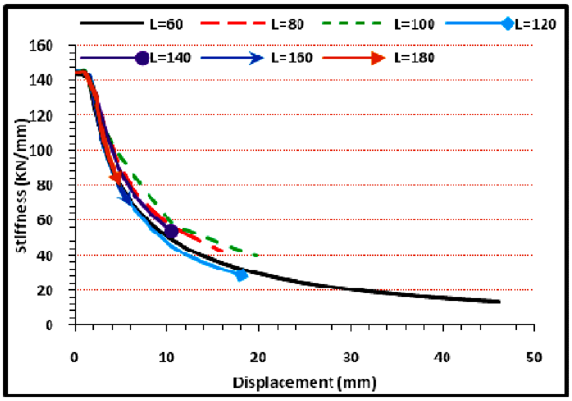

Figure 36: Performance of stiffness curves of sinusoidal corrugated plates with different corrugation length.

In Figure 37, studies of four specimens with trapezoidal corrugated plate show that the ultimate bearing and ductility decreased with increased corrugation length of the plate. Figure 38 shows that energy dissipation decreased with increased corrugation length of plate. According to Figure 39, the stiffness performance increased with increased corrugation length of trapezoidal corrugated plate, but the process of losing stiffness is shorter, as is the deformation of wall. This was due to energy dissipation decreasing.

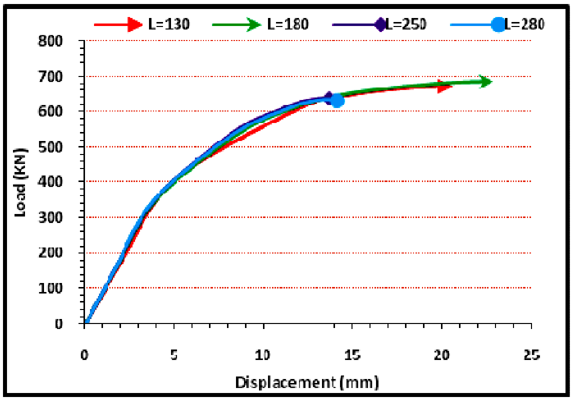

Figure 37: Load- displacement curves of trapezoidal corrugated plates with different corrugation length.

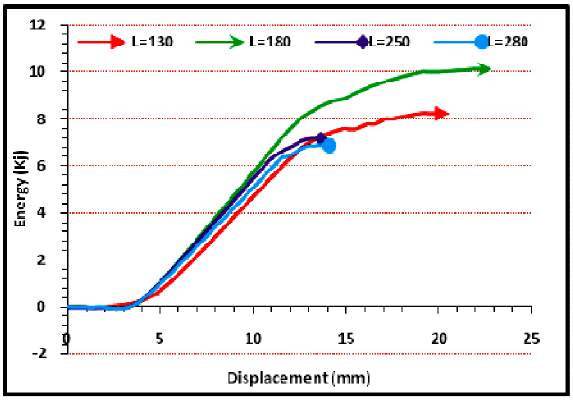

Figure 38: Energy- displacement curves of trapezoidal corrugated plates with different corrugation length.

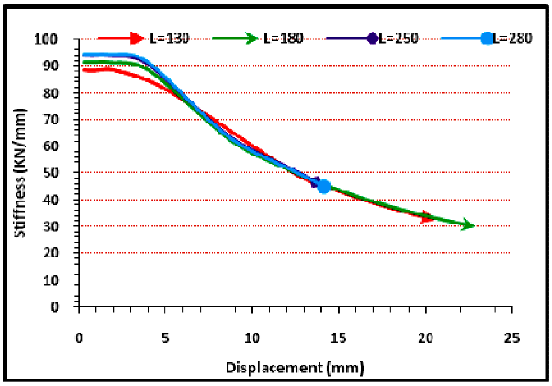

Figure 39: Performance of stiffness curves of trapezoidal corrugated plates with different corrugation length.

4.5 Comparison behavior of corrugated plates with similar corrugation density

Based on the results of different parameters on steel shear wall behaviour with sinusoidal and trapezoidal corrugated plates, in this part, the behaviour of two types of plate with similar depth, length and corrugation density have been compared. Sinusoidal and trapezoidal corrugated plates with different thickness of 3, 5, 8, 10, 12 and 15 mm were used for this comparison. The results for the uniform load for these specimens are shown in Figures 40, 41, 42 and 43.

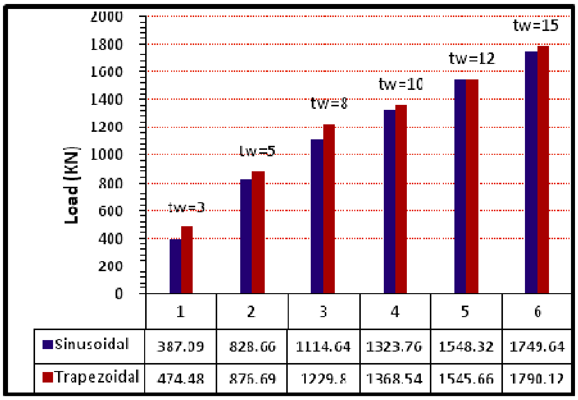

Figure 40: Comparison ultimate bearing of sinusoidal and trapezoidal corrugated plates.

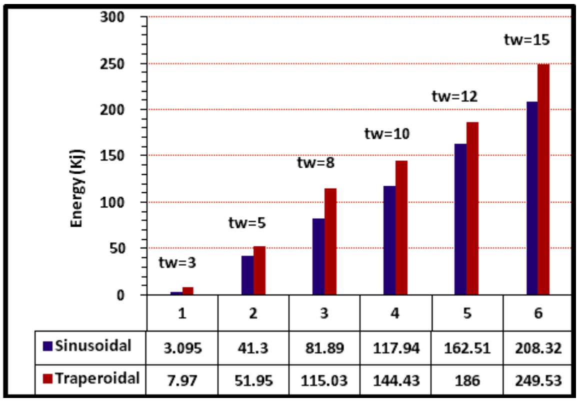

Figure 41: Comparison energy dissipation of sinusoidal and trapezoidal corrugated plates.

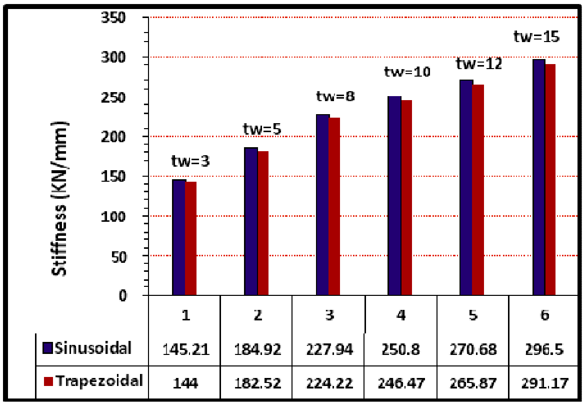

Figure 42: Comparison stiffness of sinusoidal and trapezoidal corrugated plates.

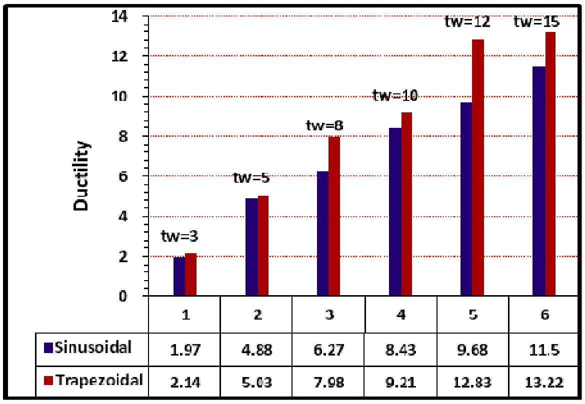

Figure 43: Comparison ductility of sinusoidal and trapezoidal corrugated plates.

These results demonstrate that for plates with similar weight and geometric characteristics, the ultimate bearing, energy dissipation and ductility show an increasing trend with increasing plate thickness. However, comparing these plates shows that the trapezoidal corrugated plate has better behaviour as demonstrated through better ultimate bearing, ductility and energy dissipation values. Furthermore, the sinusoidal corrugated plate has slightly more stiffness than the trapezoidal corrugated plate.

5 CONCLUSION

In this paper, an investigation into the geometric characteristics of sinusoidal and trapezoidal corrugated one-storey steel shear wall when subject to uniform lateral load was carried out. The following results were obtained:

1. With increasing corrugated plate thickness in steel shear walls, the ultimate bearing, ductility and energy dissipation increase significantly. The results obtained for sinusoidal and trapezoidal types of corrugated plates with similar corrugation depths show that increasing the plate thickness in sinusoidal plates produces greater stiffness and ultimate bearing compared to trapezoidal plates, but the ductility of trapezoidal plate increased with thickness changes.

2. The stiffness effects of boundary elements such as beams and columns show that increased stiffness in the elements leads to increasing trends in the ultimate bearing, ductility and energy dissipation. These changes are in the order of 3 % to 15 %, but do not have a considerable effect on the stiffness of the steel wall as a whole.

3. The other parameter investigated in this paper was the corrugated depth. The corrugated depth has greater effects on stiffness, ultimate bearing and energy dissipation of the sinusoidal plates compared to the trapezoidal corrugated plates.

4. The corrugation density coefficient is one of the important parameters of both plates. The changes in this parameter had more effect on the sinusoidal plate, so that increasing this parameter caused a significantly increasing trend in stiffness, ductility and ultimate bearing.

5. The study of corrugation length in the corrugated plates shows that the ultimate bearing is deceased with increases in the corrugation length, but also that length has no effect on the stiffness of the sinusoidal plate. However, the stiffness of the trapezoidal plate increases with increased corrugated length and the ductility is decreased.

6. The comparison of the results obtained for sinusoidal and trapezoidal corrugated plate show that the trapezoidal corrugated plates have better performance and are the corrugated plate needed for steel shear walls with specific weight, thickness, corrugation depth and length, and will ensure better ultimate bearing, energy dissipation, ductility and stiffness.

Reference

ANSYS, VER 10, Software and Reference Manuals (Theory, Elements, Analysis Guide, and Components). AS IP Inc.

Astaneh-Asl, A., (2001). Seismic Behavior and Design of Steel Shear Walls. Steel TIPS Report.

Behbahanifard, M.R., Grondin, G.Y., Elwi, A,E., (2003). Experimental and numerical investigation of steel plate shear walls. Structural engineering report No. 254. Edmonton (Canada): Department of Civil and Environmental Engineering, University of Alberta.

Berman, J., Bruneau, M., (2003). Plastic Analysis and Design of Steel Plate Shear Walls. Journal of Structural Engineering 129(11): 1448–1456.

Berman, J.W., (2011). Seismic behavior of code designed steel plate shear walls. Engineering Structures 33(1): 230-244.

Berman, J.W., Bruneau, M., (2005). Experimental investigation of light-gauge steel plate shear walls. Journal of Structural Engineering 131(2): 259-267.

Bhowmick, A.K., Grondin, G.Y., Driver, R.G., (2011). Estimating fundamental periods of steel plate shear walls. Engineering Structures 33(6): 1883-1893.

Bruneau, M., Bhagwagar, T., (2002). Seismic retrofit of flexible steel frames using thin infill panels. Engineering Structures 24(4): 443-453.

Chen, S.-J., Jhang, C., (2011). Experimental study of low-yield-point steel plate shear wall under in-plane load. Journal of Constructional Steel Research 67(6): 977-985.

Choi, I.-R., Park, H.-G., (2010). Hysteresis model of thin infill plate for cyclic nonlinear analysis of steel plate shear walls. Journal of structural engineering 136(11): 1423-1434.

Chosa, K., Kashiwai, Y., Kono, S., Watanabe, F., (2006). Fundamental study on corrugated steel webs used as shear walls. Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan.

Clayton, P.M., Berman, J.W., Lowes, L.N., (2011). Seismic design and performance of self-centering steel plate shear walls. Journal of structural engineering 138(1): 22-30.

De Matteis, G., Formisano, A., Panico, S., Mazzolani, F., (2008). Numerical and experimental analysis of pure aluminium shear panels with welded stiffeners. Computers & Structures 86(6): 545-555.

Driver, R.G., Kulak, G.L., Kennedy, D.J.L., Elwi, A.E., (1998). Cyclic Tests of Four-Story Steel Plate Shear Wall. Journal of Structural Engineering 124(2): 112-120.

Elgaaly, M., Hamilton, R., Seshadri, A., (1996). Shear Strength of Beams with Corrugated Webs. Journal of Structural Engineering 122(4): 390-398.

Elgaaly, M., Seshadri, A., Hamilton, R., (1997). Bending Strength of Steel Beams with Corrugated Webs. Journal of Structural Engineering 123(6):772-782.

Formisano, A., (2006). Experimental-numerical investigation on stiffened aluminum shear panels. Pollack Periodica 1(3): 57-77.

Galambos, T.V., (1998). Guide to stability design criteria for metal structures, 5th ed., John Wiley and Sons, NY, USA.

Gentilinia, C., Seffenb, K.A., Guest, S.D., Nobile, L., (2008). On the Behavior of Corrugated plates in Bending. Procedia Engineering 1: 79–82.

Kiymaz, G., Coskun, E., Cosgun, C., Seckin, E., (2010). Transverse load carrying capacity of sinusoidally corrugated steel web beams with web openings. Steel and Composite Structures 10(1): 69-85.

Kovesdi, B., (2010). Patch loading resistance of girders with corrugated webs. Doctor of Philosophy Thesis, University of Stuttgart, Germany.

Qu, B., Bruneau, M., Lin, C.-H., Tsai, K.-C., (2008). Testing of full-scale two-story steel plate shear wall with reduced beam section connections and composite floors. Journal of structural engineering 134(3): 364-373.

Sabouri, G.S., Gholhaki, M., (2008). Ductility of thin steel plate shear walls. Asian Journal of civil engineering (Building and housing) 9(2): 153-166.

Sause, R., Braxtan, T.N., (2011). Shear strength of trapezoidal corrugated steel webs. Journal of Constructional Steel Research 67(2): 223-236.

Sayed-Ahmed, E.Y., (2001). Behaviour of Steel and/or Composite Girders with Corrugated Steel Webs. Canadian Journal of Civil Engineering 28 (4): 656-672.

Sayed-Ahmed, E.Y., (2007). Design aspects of steel I-girders with corrugated steel webs. Electronic Journal of Structural Engineering 7: 27-40.

Sayed-Ahmed, E.Y., (2005). Plate girders with corrugated steel webs. AISC Engineering Journal 42(1): 1-13.

Stojadinovic, B., Tipping, S., (2007). Structural testing of corrugated sheet steel shear walls. Research report University of California, Berkeley.

Szilard, R., (2004). Theories and Applications of Plate Analysis. John Wiley & Sons, Inc.

Tanaka, Y., Ichioka, Y., Kono, S., Ohta, Y., Watanabe, F., (2008). Precast Prestressed Portal Frames with Corrugated Steel Panel Dampers. The 14th World Conference on Earthquake Engineering, China.

Usman, F., (2001). Shear Buckling of trapezoidal plate. Master of Science thesis, University Technology Malaysia.

Wang, X., (2003). Behavior of steel members with trapezoidally corrugated webs and tubular flanges under static loading. Theses of Doctor of Philosophy, Drexel University