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Finite Element Method for Static Cyclic Behavior of Steel Shear Wall with Corrugated Plates

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Abstract

The system of steel shear wall is an initiative resistance system against the lateral load such as an earthquake and the wind that has been researched in the last three decades. Currently, this system is noticed more than other systems because of adequate stiffness, ductility, and more energy absorption. The system of steel shear wall with corrugated sheets has been offered as an innovative system, since the construction of panels for hard-set steel shear wall is expensive and also it causes the increscent of weight construction. This type of system has been developed using of hard outer plate from geometry of corrugation shape that has better buckling strength than hard-set and flat case in this study. This study is conducted to compare the strength and energy dissipation capacity of three different steel shear walls: unstiffened, trapezoidally vertical corrugated and trapezoidally horizontal corrugated under vibration load of AISC 341-10 instruction with 100mm movement. The results reveal that although the ultimate strength of the unstiffened model is nearly 17% larger compared to that of the corrugated models, energy dissipation capacity of the corrugated models are approximately 52% larger compared to the unstiffened model.

Keyword: Finite Element Method, Cyclic loading, Corrugated, Energy, Shear Wall

1. Introduction

Steel structures have been widely utilized in the building constructions in seismic hazard area due to their higher strength and ductility. Lateral load-resisting systems in steel buildings are usually designed as the moment resisting frames or braced frames. There are advantages and disadvantages for each system. For instance, the ductility of the moment frames is usually higher than that of the braced frames and the stiffness of the braced frames is usually higher than that of the moment frames. The steel shear wall is another possible option as a lateral resisting system where it is appropriate for either a new structure or as a means to retrofit an existing building. This system consists of steel plates, one story height and one bay wide connected to the adjacent beams and columns by weld, bolt or both. The plates are installed in one or more bays for the full height of the building. The surrounding steel frame can be applied with either simple or moment-resisting beam-to-column connections. A properly designed steel shear wall has very ductile behavior and relatively large energy dissipation capacity. Furthermore, the steel shear wall as an efficient and economical lateral load resisting option has high initial stiffness and is highly effective in limiting the lateral drift of structures. When moment-resisting beam-to-column connections are present in this system, it has inherent redundancy and significant energy dissipation [1].

Numerous researches on the steel shear wall have been conducted. The experimental studies on the thin steel shear walls have been performed under cyclic loading [1–3]. Moreover, the analytical studies on the shear buckling characteristics and behavior of the multi-story thin steel shear wall have also been conducted [4–11]. Shear buckling behavior of the steel plate is the main concern of the thin steel plate shear wall. The buckling behavior of the shear panel can transform from global to local or interactive buckling by adding stiffeners. Therefore, the steel shear wall is applied in two types, stiffened and unstiffened. The stiffened type has higher stiffness and strength. Furthermore, stiffening the panel can heavily increase the amount of energy

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dissipated under cyclic loading [12,13]. However, in the stiffened system, the construction cost is considerably higher.

In this study, trapezoidally corrugated steel shear wall is investigated as a new option. This type of steel shear wall has larger buckling strength due to out-of-plane stiffness. Presently, trapezoidally corrugated plates are utilized as web of plate girders. Their shear buckling strength is described as interactive shear buckling. The research on the shear buckling behavior of the corrugated plates has been initiated by Easley and McFarland [14]. Afterwards, numerical and experimental studies on the buckling behavior and strength of the corrugated webs have been conducted by Elgaaly et al. [15, 16], Sayed-Ahmed [17] and Yi et al. [18]. Despite the significant research, the shear buckling characteristic of the trapezoidally corrugated webs has not been clearly explained. However, the value of the interactive shear buckling is affected by global, local and yield stress of the corrugated webs.

Totally, the corrugated steel shear walls are considered as improved option due to the following reasons such as local or interactive buckling in return of global buckling, more initial stiffness, more out-of-plane stiffness, lower construction cost and accordion behavior of corrugated panels. All models were similar in thickness and specification of boundary frames as well as their connections. In order to initiate the simulation of the steel shear walls as in the real world practice, no special or unusual fabrication techniques were employed. All models were fixed at the bottom and had moment-resisting beam-to-column connections. The tests were conducted according to an approved method for the simulation of seismic loads [19].

2. Finite element modeling

Totally, three models were designed and constructed to investigate and distinguish the cyclic behavior of the trapezoidally vertical and horizontal corrugated steel shear walls with unstiffened steel shear wall. The first model was an unstiffened steel shear wall and the second model was the trapezoidally vertical corrugated and the third model was the trapezoidally horizontal corrugated steel shear wall. Boundary frames in the corrugated models were considered to be similar to that of the first model in order to provide the opportunity to compare the seismic behavior of the models. Furthermore, the applied shear plates in all the models were similar in both panel thickness and mechanical properties; however, they just turned into the trapezoidal form for the corrugated models. Geometric properties of the corrugated panels are shown in Fig. 1.

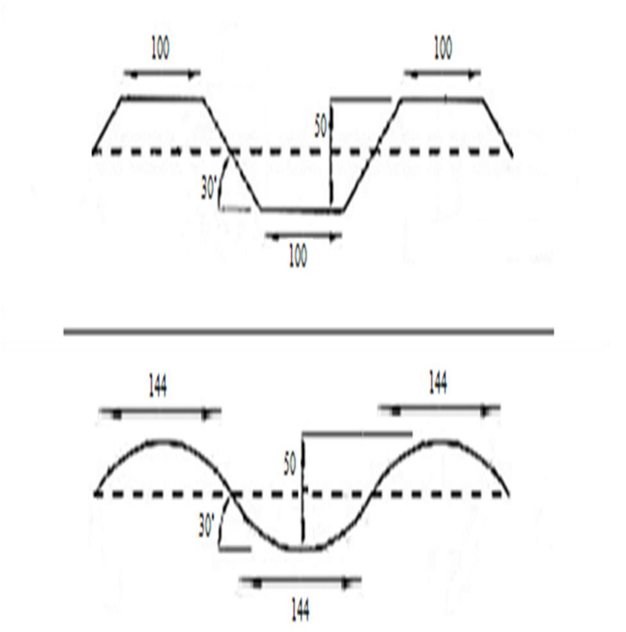


Fig. 1. Geometric properties of trapezoidally corrugated plate (mm).

The details of the tested models are shown in Figs. 2. In each model, the top beam section is IPB140 and the section of columns is IPB160. The bottom beam section in each model is IPB200. The dimensions of the panel in each model are 1480*1980 with thickness of 1.25 mm. The summary of design models is listed in Table 1.

Mechanical properties of the steel plates and the steel profiles applied in the construction of the models are reported in Table 2. The mechanical properties were determined by coupon test performed according to the ASTM E8M-04 and DIN Standard [20,21]. The connection of each column to the bottom beam and top beam to the columns was moment-resisting. Boundary conditions which are applied to the edges can be defined as follows: Clamped Boundary Conditions: ($u = v = w = \theta x = \theta y = \theta z = 0$), where u, v and w are displacements along X, Y and Z directions, respectively. Also θx, θy and θz are rotations about X, Y and Z directions, respectively.

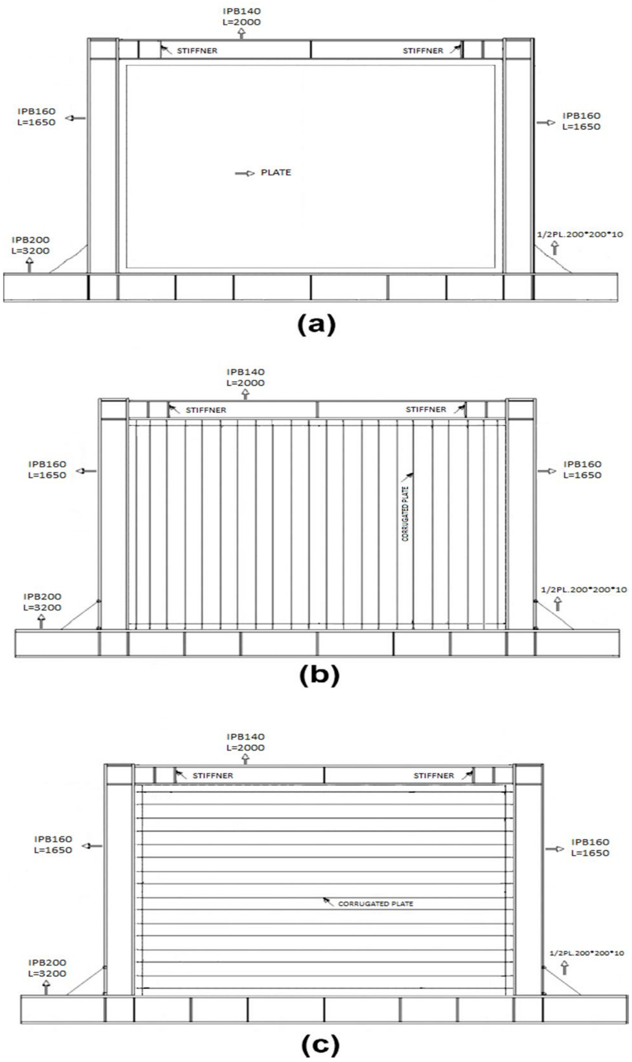


Fig. 2. Model no. 1,2,3 (mm)

Table 1
Design of models (unit: mm).

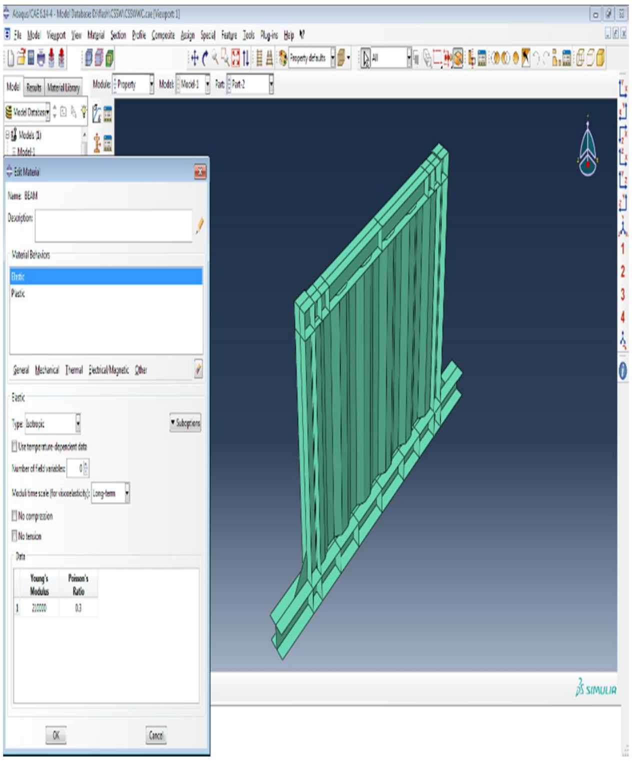
Beam	Models	Column	Plate thickness	Type panel
No. 1	IPB140	IPB160	1.25	Unstiffened
No. 2	IPB140	IPB160	1.25	Vertical corrugated
No. 3	IPB140	IPB160	1.25	Horizontal corrugated

Table 2
Mechanical properties.

Type	Young's modulus E (GPa)	Yield Stressf (MPa)	Ultimate Stress f_y (MPa)	Percent elongation (%)
Plate	210	207	290	41
Column	210	300	443	33
Beam	210	288	456	37

FE model of the steel shear wall with corrugated plates is constructed with 3D model in the ABAQUS. For FE modeling, first the area is meshed then the area extruded with iso parametric brick elements solid along the longitudinal direction.

The FE model is shown in Fig. 3.



Name: BEAM

Description:

Material Behaviors: Elastic, Plastic

Elastic

Type: Isotropic

☐ Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

☐ No compression

☐ No tension

Data

	Young's Modulus	Poisson's Ratio
1	210000	0.3

Fig. 3. FE model

To simulate earthquake load and further to investigate thecyclic behavior, they use gradual increasing loads or displacements in successive cycles [22]. AISC341-10 protocol was applied in order to obtain a more logical evaluation of the cyclic behavior. In this study, loading was conducted as displacement, and gravity loads were not applied. The described procedure of cyclic loading is shown in Fig. 4.

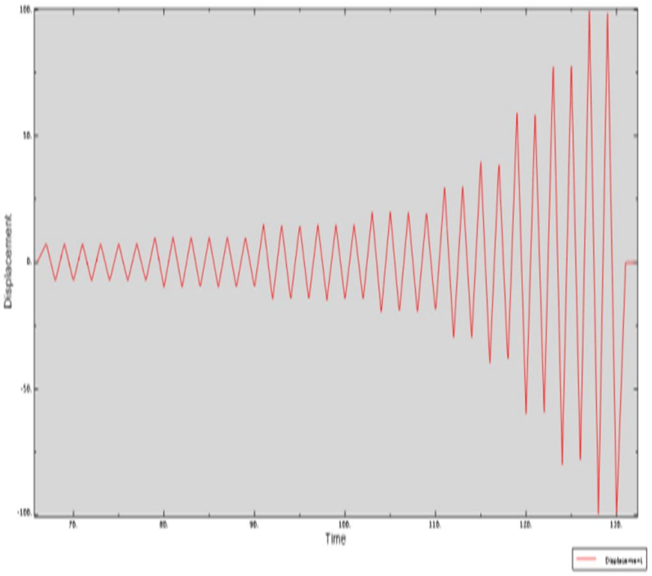


Fig. 4. Standard Loading History in ABAQUS, AISC341-10 [22]

3. Results and discussions

The energy dissipation capacity and ultimate strength are the main characteristics which affect the seismic performance of the steel shear wall. In this research, for each model, the value of the wall strength decreased relative to the ultimate strength with increasing displacement amplitude, or when displacement amplitude reached 100 mm. Hysteretic behaviors of all the models are shown in Fig. 5. Further, Fig. 6 indicates the typical deformation pattern after the analyzing. Although hysteretic behavior of the unstiffened and corrugated models along with their load distribution pattern was different, eventually all the models failed after significant inelastic tension field action occurred with a large story drift deformation. In addition, in both corrugated models unlike the unstiffened model, the total capacity of the panel was utilized so that yielding and tearing were observed in most of the shear panel positions. Using the cyclic loading results, the elastic and ultimate strength of each steel shear wall system under monotonic loading is calculated. The amount of applied load for occurring the first yielding in the steel shear wall system is nominated as the elastic strength and the maximum applied load is nominated as the ultimate strength.

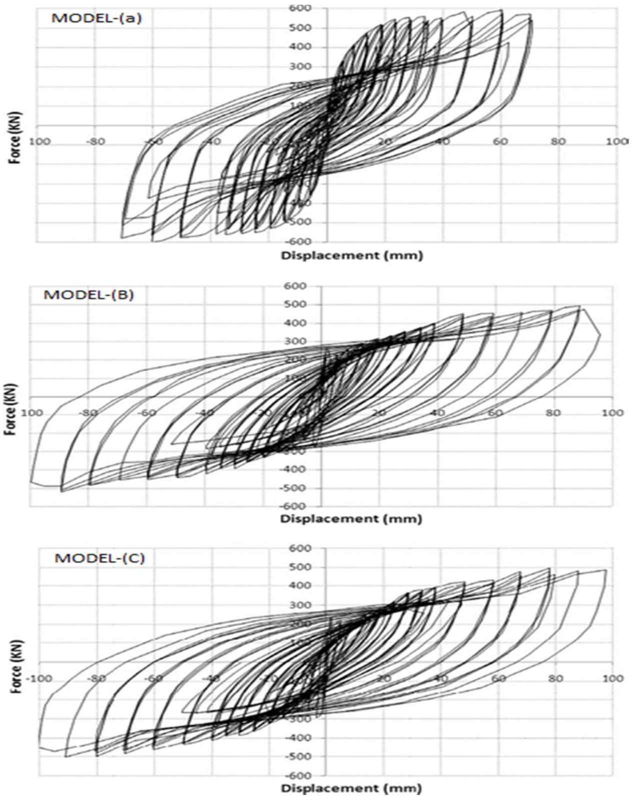


Fig. 5. Hysteresis behavior of the analyzed models

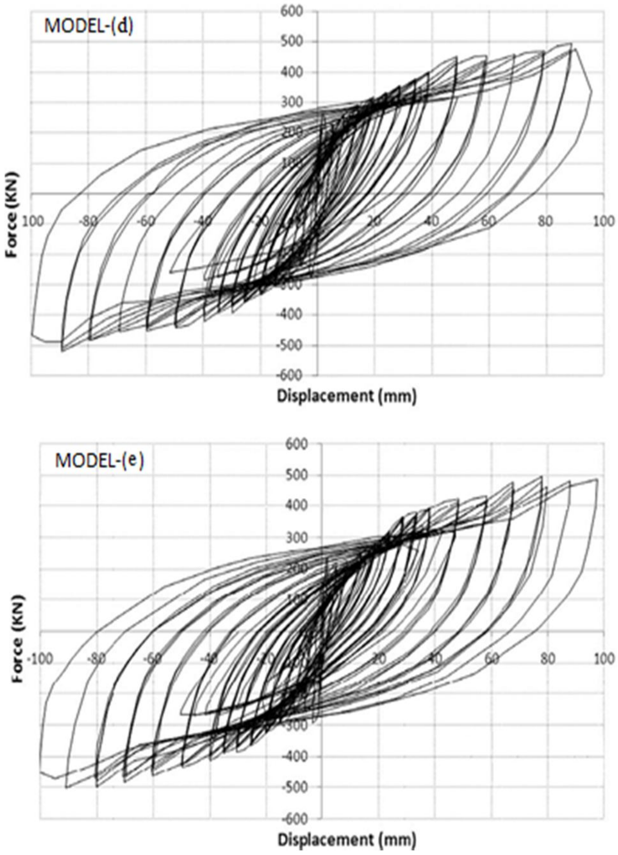


Fig. 5. Hysteresis behavior of the analyzed models.

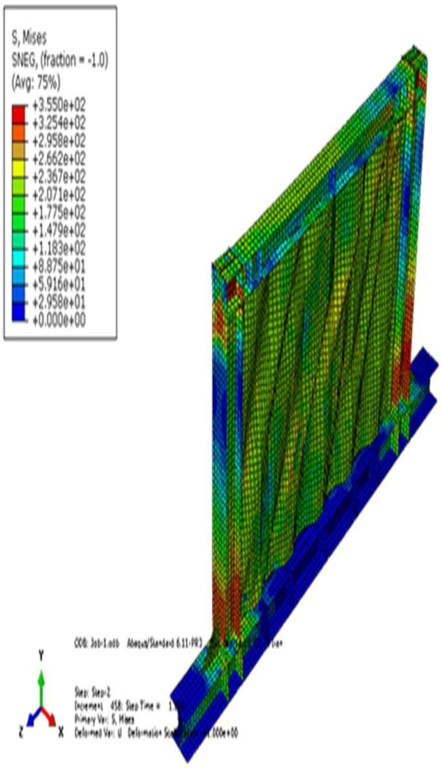


Fig. 6. State of model at ultimate stage: Model-(b)

The strength-drift angle relations of all systems are shown in Fig. 7. This figure indicates that elastic strength and the ultimate strength of the tested corrugated models are similar and elastic strength of the model nos. 2 and 3 is nearly 15% larger compared to the model no.1 whereas the ultimate strength of the model no.1 is about 17% larger than that of the corrugated models. It is believed that the lower inelastic strength of the corrugated models is due to their accordion behavior. In fact, after inelastic buckling, in-plane stiffness of the corrugated panels decreased abruptly in direction of corrugations. Therefore, the tension field in the corrugated models formed incompletely. To design steel plate shear walls, designer should take into consideration to ensure that the steel plate does yield prior to the boundary beams and columns. In fact, the boundary frame is designed to remain elastic as long as it is possible. Thus, by this procedure, the system is able to maintain stability even after the failure of the shear panel.

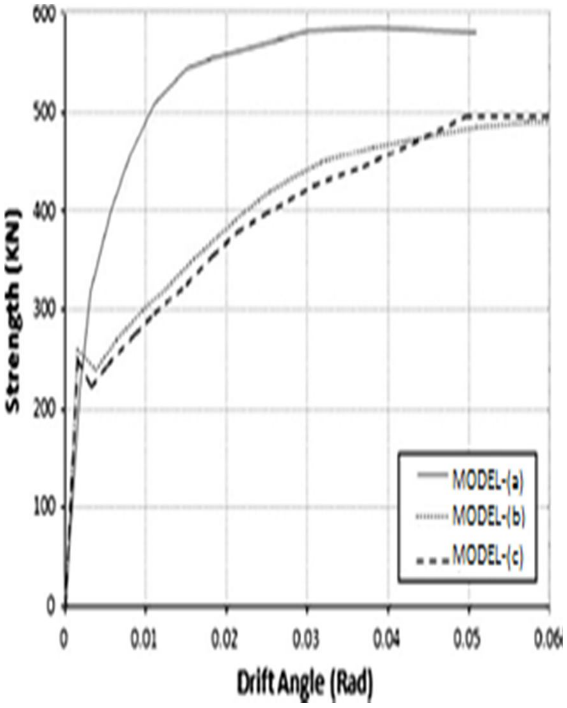


Fig. 7. Strength of models under monotonic loading.

The amounts of energy dissipated because of the seismic load are major parameters in the lateral load resisting systems. As it was illustrated in Fig. 5, although all the models dissipate the energy with stable hysteresis loops, there is pinching in the hysteresis loops of the unstiffened model. Both of the corrugated models are able to dissipate more energy as oppose to the unstiffened model. The cumulated energy at various drift angles are illustrated in Fig. 8. The model nos. 2 and 3 dissipate nearly the same energy in different drift angles. The structural analyzing of the model no. 1 was stopped at 4.5% drift angle due to the decrease of strength whereas the cyclic testing of the model nos. 2 and 3 continued up to 6.4% drift angle. Although the ultimate strength of the unstiffened model is about 17% larger than that of the corrugated models, energy dissipation of the corrugated models are approximately 52% larger than those of the unstiffened model, respectively.

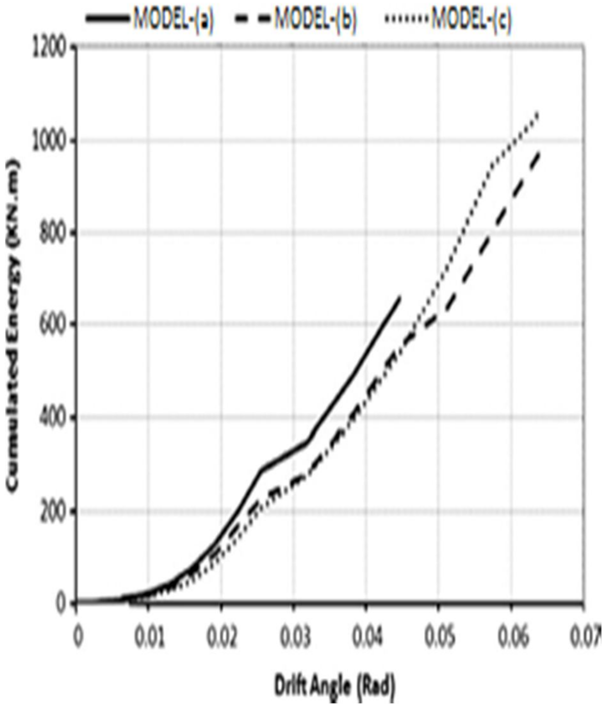


Fig. 8. Cumulated energy of models.

According to the performance-based design concept, at the ultimate failure stage, the story drift angle is about 2.5–3% [23,24].

This research demonstrates that by the proper design, the corrugated steel shear walls can achieve 5–7% story drift angle, whereas story drift angle does achieve 3–5% for the unstiffened steel shear walls. Besides, from the hysteretic behavior under quasi-static loading, it is realized that the characteristics of the corrugated steel shear walls are more stable as opposed to the unstiffened steel shear wall.

4. Conclusions

The corrugated steel plate carries high out-of-plane stiffness and high elastic shear strength. The corrugated steel shear wall is able to dissipate the seismic energy through plastic deformation without any pinching in the hysteretic loops. The ultimate story drift angle can be as large as 5–7% in this system. The study indicates that the total energy dissipation of the corrugated models is approximately 1.52 times higher than that of the unstiffened model.

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