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Effect of Corrugation Angle and Direction on the Performance of Corrugated Steel Plate Shear Walls

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Abstract

Corrugated steel plate shear wall (CSPSW) is one of the lateral resistance systems which consists mainly of steel frame (beam and column) with vertical or horizontal corrugated steel plate connected to the frame by weld, bolts or both. This type of steel shear wall characterized by low cost and short construction time with high strength, ductility, initial stiffness and excellent ability to dissipate energy. The aim of this paper is to evaluate the effect of corrugation angle and its direction on the performance of CSPSW under cyclic loading. The Finite element analysis was employed to achieve the research aim. The FE models were validated with experimental data available in the literature. Results reveal that the corrugation angle has a clear influence on initial stiffness, strength, ductility, and energy dissipation of CSPSW. The optimum performance of CSPSW can be obtained with angles of 30º for CSPSW with vertical corrugation and 20º for CSPSW with horizontal corrugation. The use of CSPSW with vertical corrugation provides higher strength, stiffness, and ductility compared to CSPSW with horizontal corrugation. Therefore, it is recommended to use CSPSW with vertical corrugation.

Keywords: Corrugated Shear Wall; Corrugation Angle; FEM Analysis; Cyclic Loading; AC154 Protocol; Energy Dissipation.

1. Introduction

Steel plate shear walls (SPSWs) are lateral force resisting system. They have seen increased in usage over the last thirty years. They provide significant strength, ductility and initial stiffness at relatively low cost and short construction time [1]. SPSWs always show early elastic buckling in the wall panels under gravity loads transferred from the boundary frame and floor during construction, or even under low lateral load unless they strengthened by stiffeners or concrete encasement. Therefore, there is a need for another type of shear wall that could be a viable and convenient solution without the need for welding stiffeners or casting concrete. Corrugated Steel Plate Shear Wall (CSPSW) is one of the best alternatives. CSPSW is a new type of lateral load resisting system within the family of steel plate shear walls, which consists of a steel boundary frame and a corrugated steel plate wall panel. The corrugated plate categorized by three aspects: angle of corrugation, horizontal side, and the inclined side, which are forming the ribs (Figure 1). The ribs are one of the advantages of the geometric shape of the corrugated plate. They act as stiffeners to the plate and they proved to improve ductility, initial stiffness, energy dissipation, and the ability to oppose the gravity loads compared with SPSW. In addition, CSPSWs have lower construction cost because there is no need for stiffening the plate [2]. CSPSWs can be divided according to the direction of corrugation to the vertical corrugated and horizontal corrugated steel plate shear wall.

In recent years several studies have investigated the behaviour of corrugated steel plate shear walls. Easley and McFarland [3] was the early research that conducted for studying the global shear buckling equation of corrugated plates. Mo and Perng [4] tested five specimens of the reinforced concrete frame and corrugated steel plate. The specimens tested

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under reversed cyclic loads. The study investigated the effect of the thickness of the steel plate on the performance of the shear wall. It was stated that the thick steel plate reduces the ductility. An experimental study to the structural behaviour of CSPSW was conducted by Emami and Vafai [5] for three specimens: one with simple plate and two specimens with vertical trapezoidally corrugated steel plate and horizontal trapezoidally corrugated plate shear walls. The study showed that the strength in corrugated steel plate was reduced by 17% and the ductility ratio, the energy dissipation, and the stiffness was increased by 40, 52 and 20 % respectively compared with the simple plate.

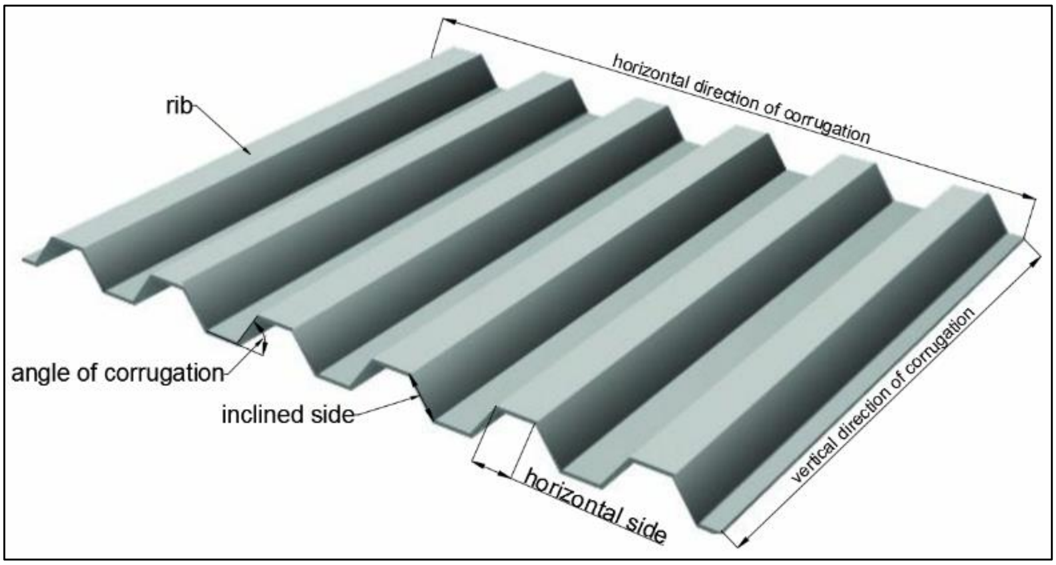

Figure 1. Details of the geometric shape of CSPSW

Farzampour and Laman [6] studied the behaviour of corrugated steel plate shear walls with openings. They found that the ductility and the initial stiffness of corrugated shear walls generally higher than those of steel shear walls, especially in relatively thinner plates. Tong and Guo [7] conducted a theoretical study to investigate the elastic buckling of trapezoidal corrugated shear walls with vertical stiffeners and used FEM to verify the proposed formulas. They claimed that the formulas of elastic buckling coefficients of stiffened trapezoidal corrugated steel plate shear walls could provide reliable buckling strength and can be used directly in the design of stiffened trapezoidal corrugated steel plate shear walls. Bahreba et al. [8] Investigated the structural performance of CSPSW for the horizontal trapezoidal corrugations with centrally-placed square opening. It was found that increasing the opening size results in reducing the initial stiffness and ultimate strength but there was no clear effect on ductility.

Hosseinzadeh et al. [9] performed an experimental investigation to the behaviour of corrugated steel plate shear walls with a different angle of trapezoidal plate. The study showed that increasing the corrugation angle results in reducing the stiffness and energy dissipation. In addition, large loss of strength was reported. Shon, Yoo and Lee [10] investigated experimentally the hysteresis behaviour and energy dissipation for the steel frame with and without corrugated steel plates. They showed that the use of the corrugated steel plates results in improving the energy dissipation capacity. Zhao et al. [2] studied the nonlinear cyclic behaviour of CSPSW and SPSW using FEM. All members were modeled using 4 nodes shell element. The research investigated the effect of different panel configurations. The study showed that the ultimate lateral strength of SPSW reduced higher than that of CSPSW with the presence of gravity loads. The CSPSW with deep corrugation has 34%, 26% and 5% initial stiffness, energy dissipation and ultimate strength respectively higher than SPSW. Hosseinzadeh et al. [11] studied the linear buckling analysis of flat and corrugated steel shear wall using finite element. They confirmed that reducing the width of the horizontal side of the trapezoidal corrugated panels can only change the buckling type from local to global without any increase in buckling strength. Cao and Huang [12] performed the experimental and numerical simulation for two specimens of the single-bay two-story frame of CSPSW. The study found that the CSPSW could avoid elastic buckling through the proper design of the corrugation parameters, and the CSPSW has higher initial stiffness, energy dissipation, strength and ductility.

Tong, Guo, and Zuo [13] studied the elastic buckling and load-resistant of double corrugated steel plate shear walls using finite element and compared the results with the theoretical formulas of the rigidity constants. The study investigated the effect of aspect ratios, the thickness of the corrugated plate, depth of corrugation, the angle of corrugation, and the corrugation wavelength. The consequences of the investigation allude to three kinds of elastic buckling: the local elastic buckling and two types of global elastic buckling. Tong and Guo [14] considered the shear resistance behaviour of stiffened CSPSW with utilizing the FE nonlinear investigations. The study stated that when the aspect ratio or the plate thickness is small, the CSPSW yields before any noticeable out-of-plane deflections in the corrugated plate. Thus slight deformation could be seen in the stiffeners, however, when the aspect ratio gets bigger the CSPSW failed by critical out-of-plane deflections over the entire board and huge out-of-plane deformation could be seen in the stiffeners.

Farzampour et al. [15] studied the seismic behaviour of the SPSW and CSPSW with varieties of corrugation geometry using FEM. The effect of corrugation angle, the opening, and the corrugation subpanel length that subjected to monotonic and cyclic loads. The results of this study reported that the corrugated steel plate with opening gives better performance from the steel plate. The angle 30° gives the best performance and the increasing the angle of corrugation leads to decreasing the stiffness and ductility but it leads to increasing the ultimate strength. Qiu et al. [16] conducted an experimental study that investigates the cyclic behaviour of the corrugated steel plate shear walls. The study consists of four specimens, the first specimen with a simple plate, the second with a vertical corrugated plate, the third with a horizontal corrugated plate, the fourth with the horizontal corrugated plate but with different corrugation geometrical details. The results of the study refer to that the specimen with corrugated plate has higher buckling stability and post yield stiffness, but lower ultimate strength from the simple plate. The direction of corrugation has no effect on the behaviour of corrugated specimens.

The literatures stated that there is a need for detailed investigation to the effect of the corrugated plate geometry on the performance of the corrugated steel plate shear walls. Such investigation needs to evaluate the weight of each parameter to provide fundamental understanding to their influence on the CSPSW performance and propose some design recommendations. Accordingly, this research was set to study the effect of the corrugation angle and direction on the performances of the corrugated steel plate shear walls and determine the angle and direction that provide the optimum performance. The influence of each parameter was evaluated through the initial stiffness, ductility, strength, and the dissipated energy.

2. Finite Element Modeling and Validation

Three dimensional finite element model was built to simulate the behaviour of the corrugated steel plate shear wall. All parts of the model (beams, columns, stiffeners and the corrugated plate) were modeled using four nodes shell element. This element has six degrees of freedom three translation in X, Y and Z directions, and three for rotation about X, Y, and Z-axes. Nonlinear isotropic/kinematic hardening was used to simulate the cyclic behaviour of the models in the plastic region. The nonlinear kinematic hardening defines the movement of the yielding surface and the isotropic hardening describes the size of the yield surface. It estimates the strain levels at different loading stages and linearizes the actual material behaviour accordingly. The bottom surfaces of the lower beam were considered fixed and nodes in the beam-column connection at the top were restricted from global-direction translation to prevent movement of frame members in the front direction as shown in Figure 2.

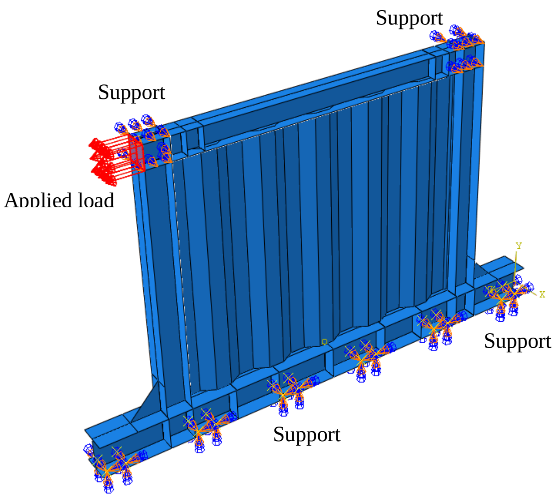

Figure 2. FM model

To assess the reliability of the FM models, the results of the numerical analysis were compared with the experimental results of Emami et al.[5] and Hosseinzadeh et al. [9]. The details of the two experimental programs are described below:

2.1. Specimens Tested by Emami et al. [5]

Two specimens of CPSPW were tested, the first was with a vertical corrugated plate (V-CSPSW) and the second was with horizontal corrugated plate (H-CSPSW). The frame consists of two steel beams (top HEB140, bottom HEB200) and two steel columns (HEB160). The corrugated plate dimensions were 1480 × 1980 mm for the two specimens with thickness of 1.25 mm. The specimens' details are shown in Figure 3. The mechanical properties of the specimens' components are listed in Table 1.

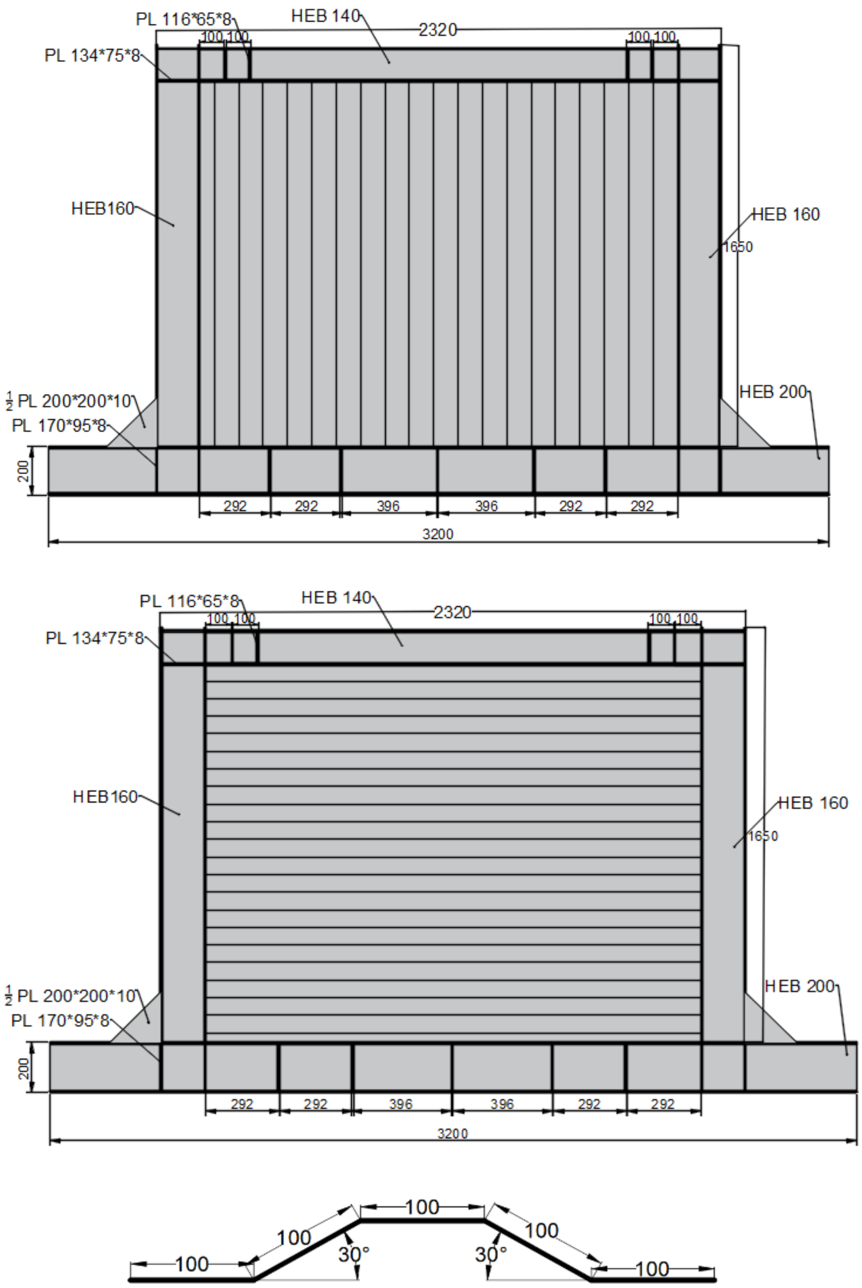

Figure 3. The details of the corrugated plate (mm) and the specimens [5]

Table 1. Mechanical properties for specimens tested by Emami et al. [5]

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

2.2. Specimens Tested by Hosseinzadeh et al. [9]

The tests were conducted for three specimens. Each specimen was built up using HEA160 for top beam and column and HEA200 for bottom beam. The corrugated plate thickness was1.25mm and the dimensions were 1480 × 1800 mm for the three specimens. The angle of corrugation was different for each specimen. It was 30° for the first specimen (CSPSW-30°), 45° for the second specimen (CSPSW-45°) and 60° for the third specimen (CSPSW-60°). The details of the three specimens are shown in Figure 4 and the mechanical properties of the specimens are presented in Table 2.

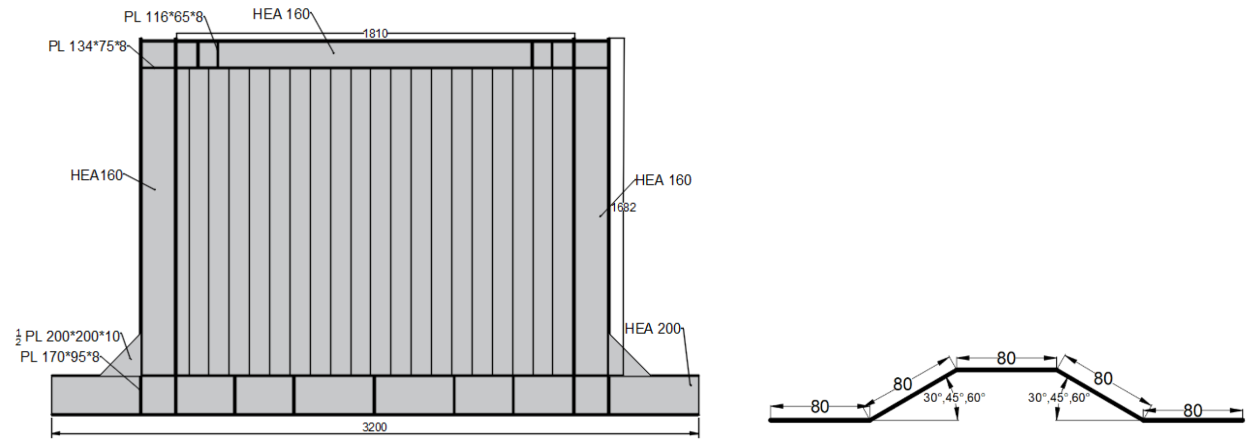

Figure 4. The details of the corrugated plate (mm) and the specimens [9]

Table 2. Mechanical properties of specimens tested by Hosseinzadeh et al. [9]

Part	Young's modulus E(GPa)	Yield stress f_y (MPa)	Ultimate stress f_u (MPa)	Percent elongation (%)
Plate	200	310	455	36.2
Frame	200	262	360	33.2

The models were loaded with horizontal cyclic loading in the top side of the model according to the history of AC 154 protocol [17] and the deflected shape principle was adopted for failure criterion. The loading protocol consists of the three cycles: 25, 50, and 75 % of the approximate elastic displacement (AED) and each cycles is repeated for three times. The last loading stage consists of three cycles: 125, 150, 175, 200, 250, 300 and 350 % of AED and each cycle followed by four cycles as shown in Figure 5.

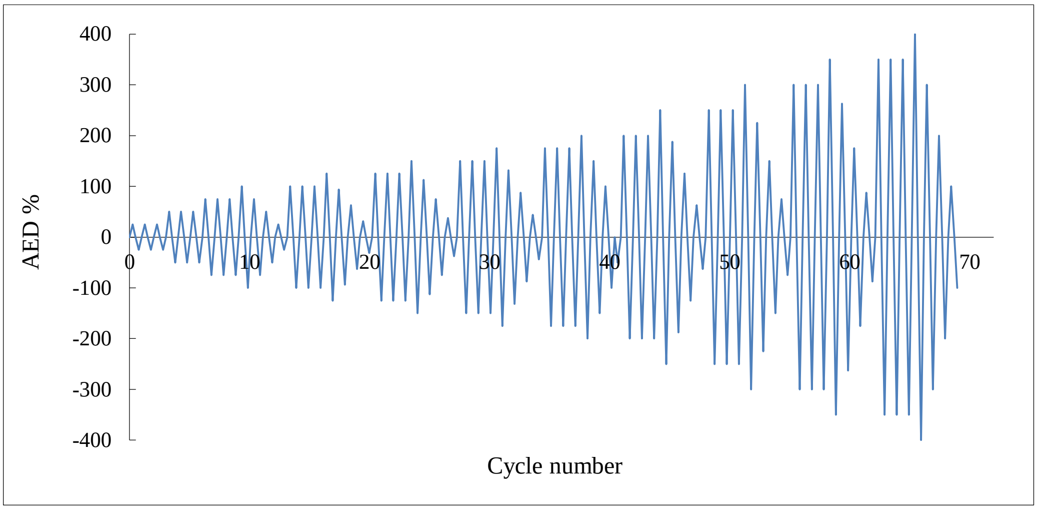

Figure 5. loading history AC154 protocol [17]

Figures 6 to Figure 9 and Table 3 show the comparison between numerical predictions and the test results. The clear agreement between the FE and the experimental data reveals the accuracy and the reliability of numerical simulations.

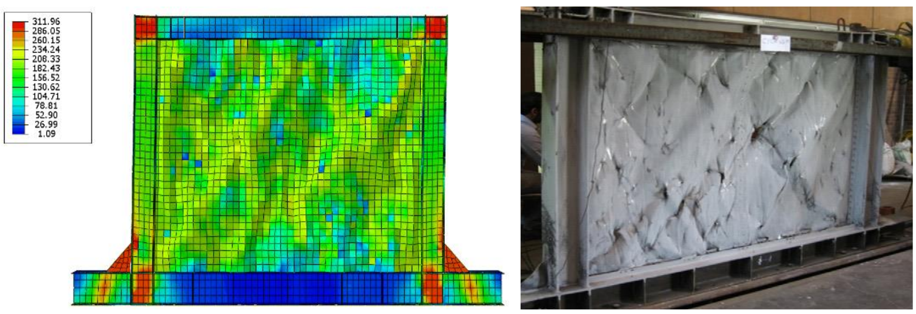

Figure 6. Deflected shape of FE analysis and deformed shape of Emami et al. [5] test (V-CSPSW)

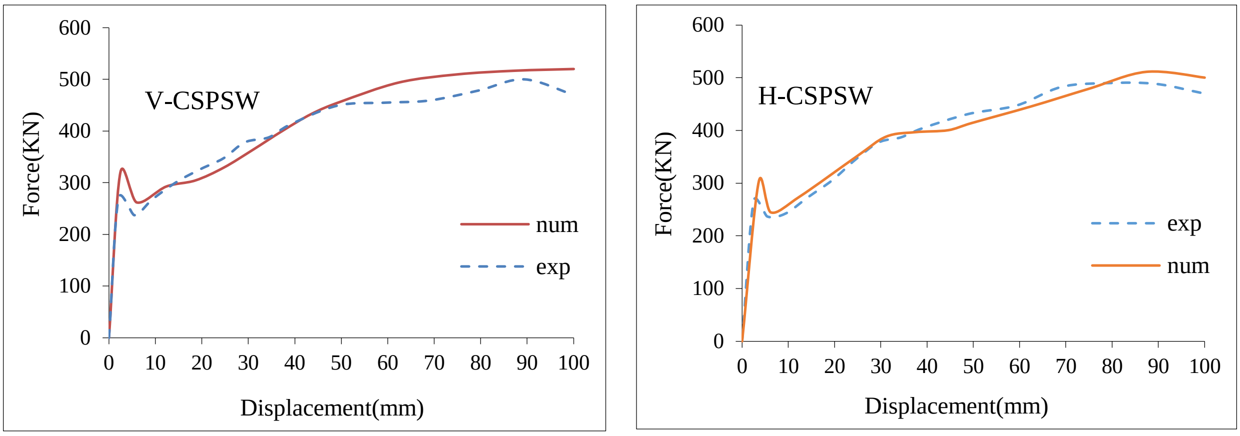

Figure 7. Load-displacement curves of numerical analysis and Emami et al. [5] test

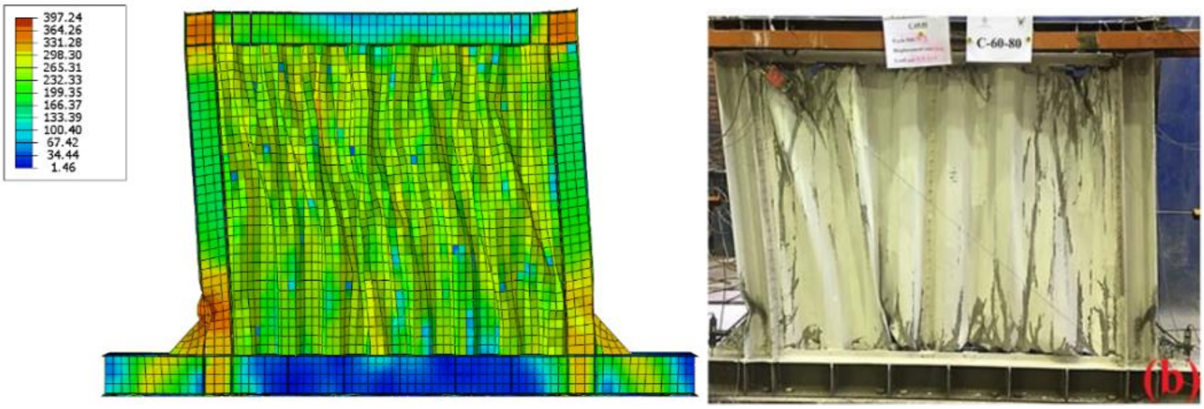

Figure 8. Deflected shape of FE analysis and deformed shape of Hosseinzadeh et al. [9] test (CSPSW-60°)

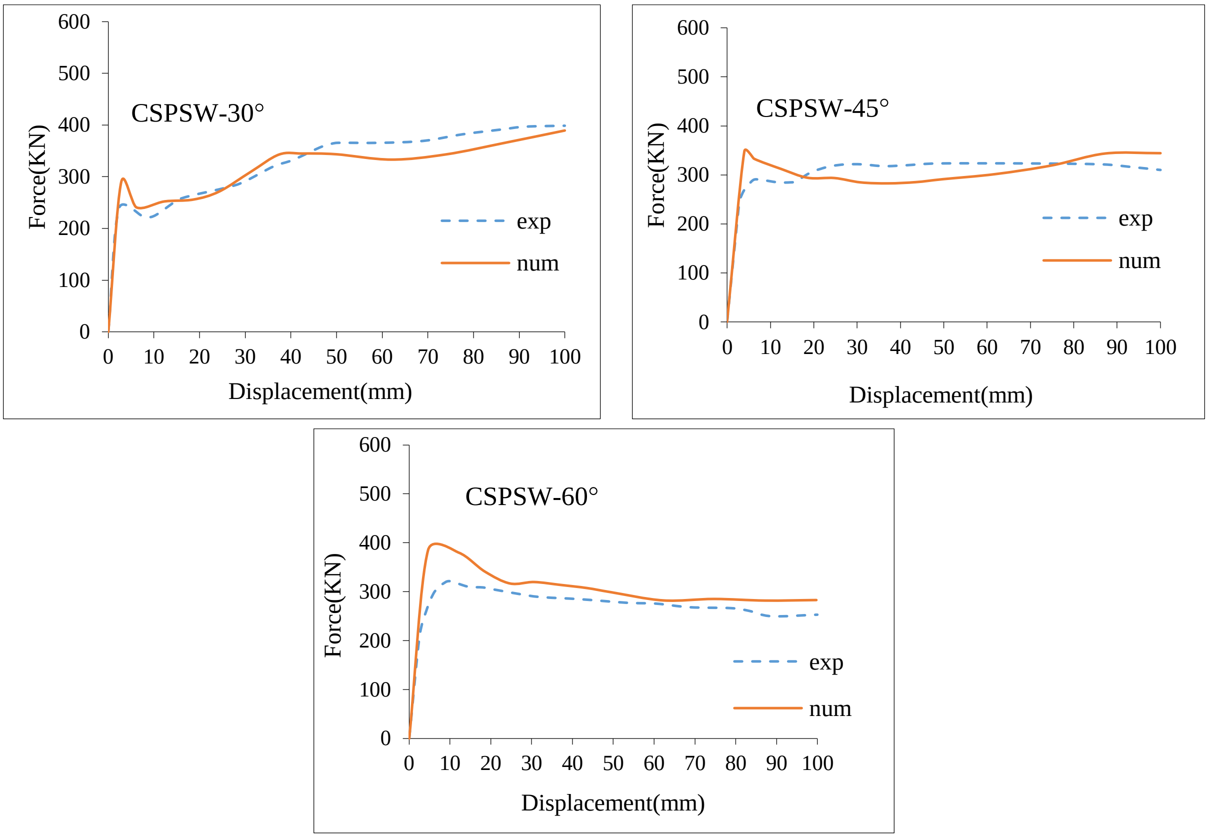

Figure 9. Load-displacement curves of numerical analysis and Hosseinzadeh et al. [9] test

Table 3. The maximum strength of Numerical and experimental test values

Specimen	Num (kN)	Exp (kN)	Num/Exp
V-CSPSW	524	500	1.048
H-CSPSW	490	511	0.958
CSPSW-30°	390	401	0.972
CSPSW-45°	348	323	1.077
CSPSW-60°	385	322	1.195

3. Parametric Analysis

The influence of the corrugation angle on the performance of CSPSW was investigated by changing it from 10˚ to 90˚. The effect of the direction of corrugation (vertical or horizontal) was also investigated. The performance of the CSPSW was evaluated according to the initial stiffness, ductility ratio, and the strength and energy dissipation.

3.1. Hysteresis and Envelop Curves

Hysteresis curves are used as an indicator of strength and energy dissipation. The envelope curve "contains the peak loads from the first cycle of each phase of the cyclic loading and neglects points on the hysteresis loops where the absolute value of the displacement at the peak load is less than that in the previous phase" [18]. Figures 10 to Figure 18 show that with angles less than 70˚ the strength is increasing with the increase of loading cycles until it reaches its ultimate value. However, for angles between 70˚ and 90˚, the maximum strength was recorded at the first loading cycle and it starts decreasing with the increase of cycles. This scenario was repeated in both cases of the vertical and horizontal corrugation of the plate. The actual behaviour of the envelope curve can be idealized to elastic-perfectly plastic which is based on the concept of equal plastic energy, which agrees with what stated in the literature [19].

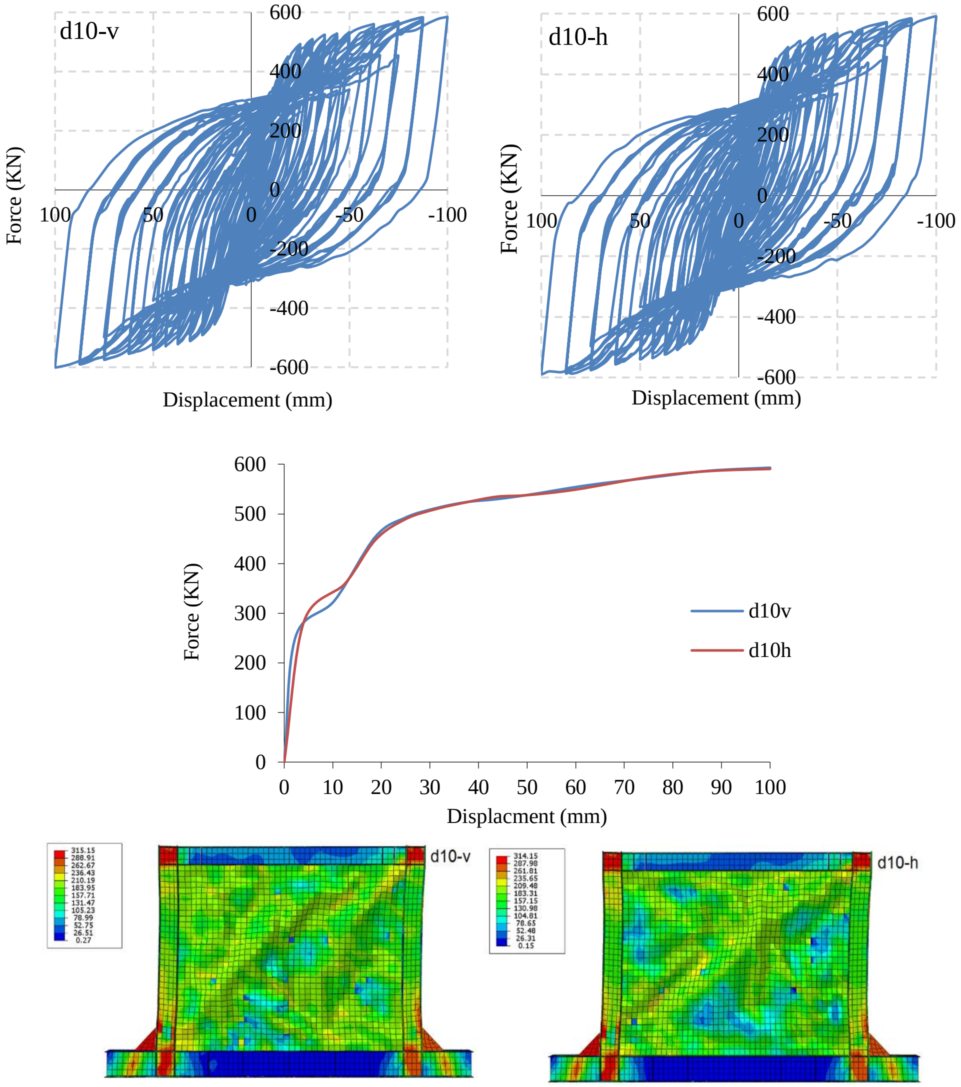

Figure 10. Hysteresis curves, envelope curve, and deflected shape for angle=10º

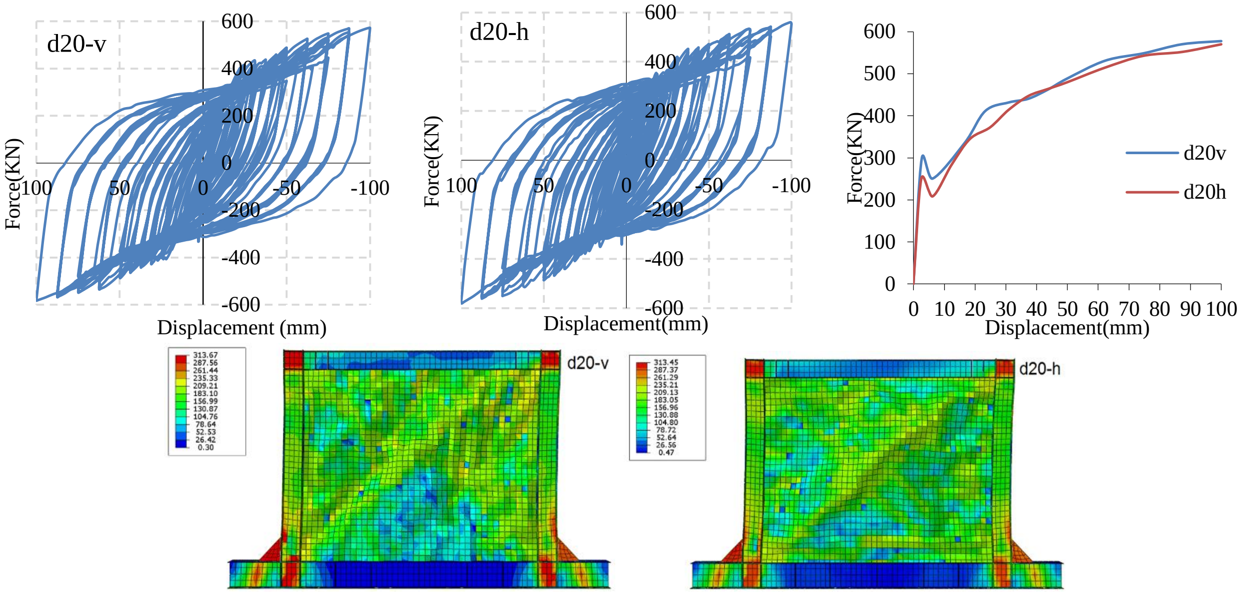

Figure 11. Hysteresis curves, envelope curve, and deflected shape for angle=20º

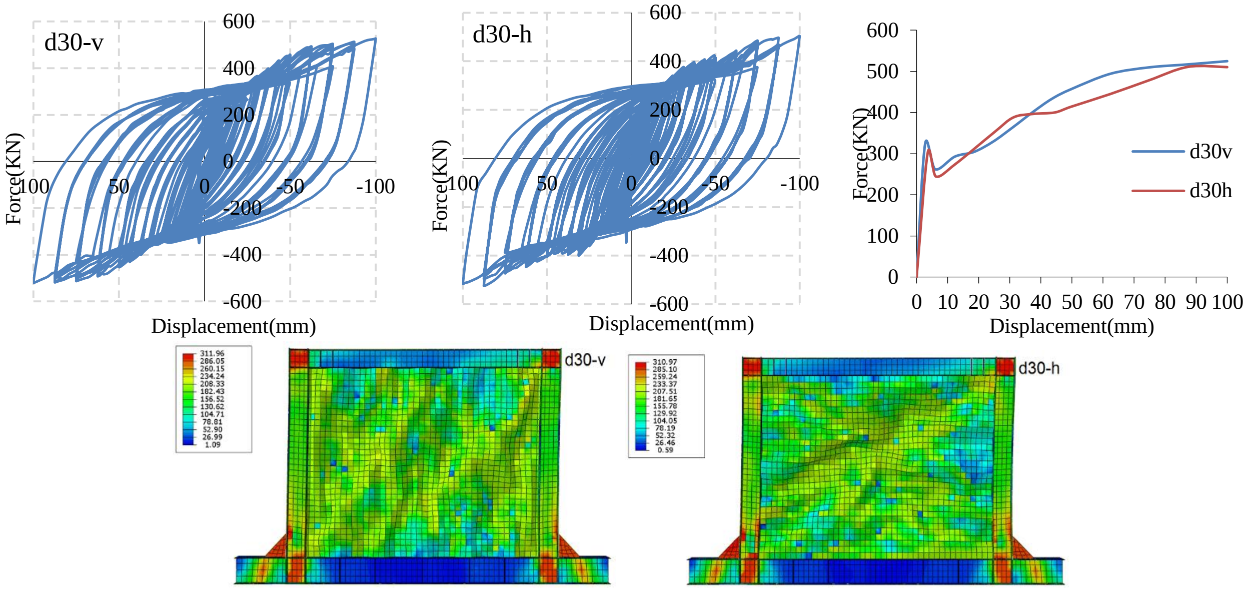

Figure 12. Hysteresis curves, envelope curve, and deflected shape for angle=30º

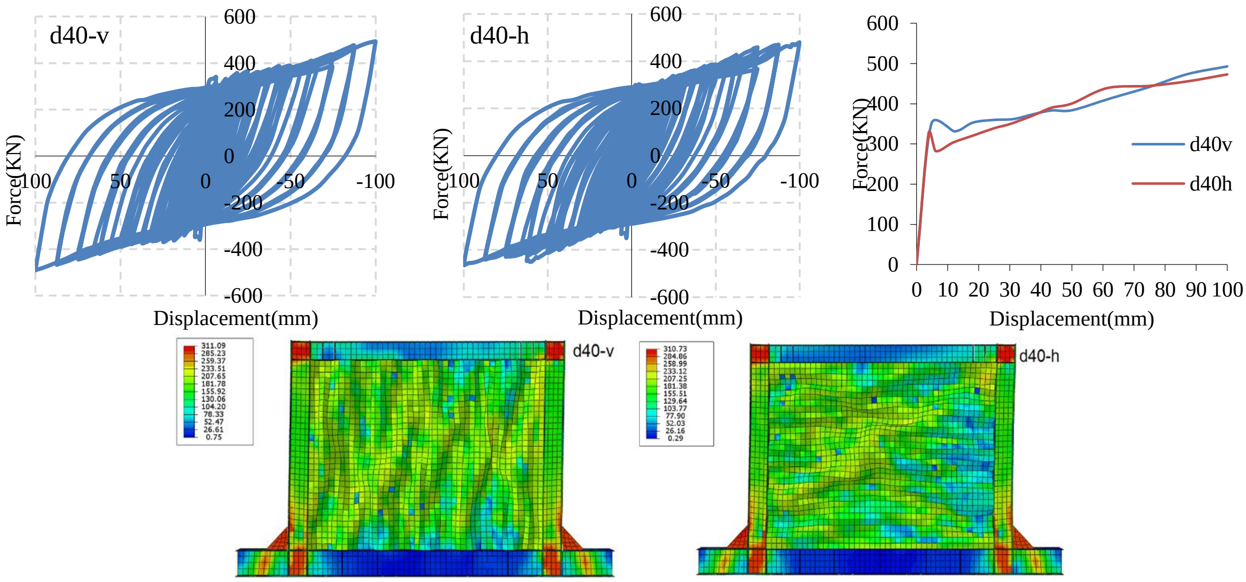

Figure 13. Hysteresis curves, envelope curve, and deflected shape for angle=40º

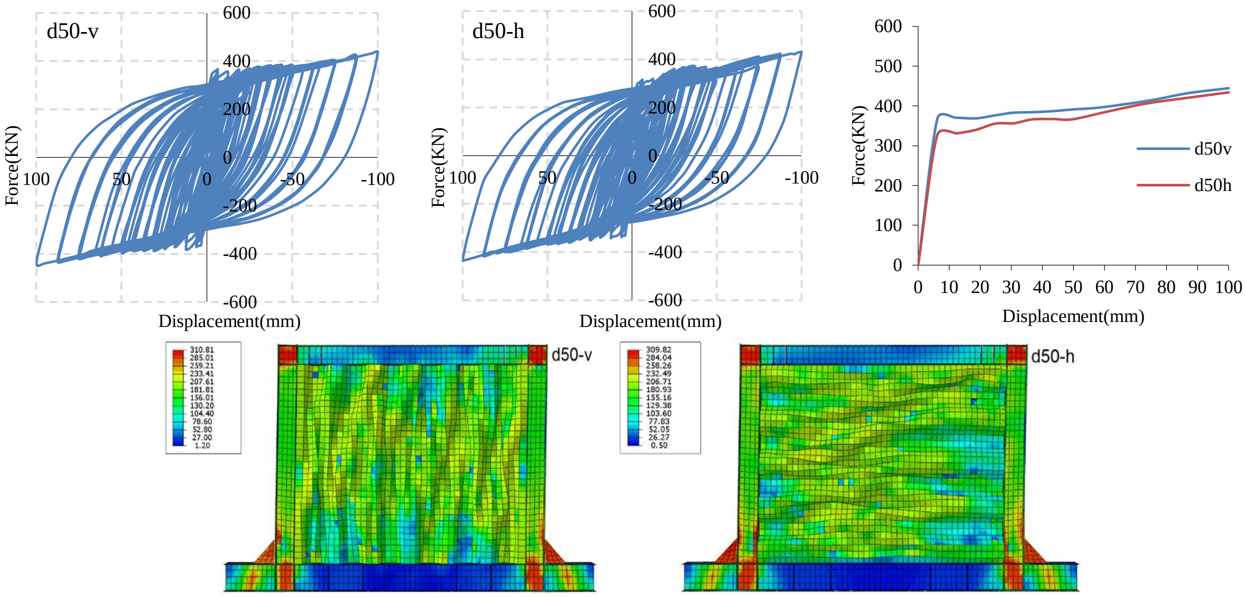

Figure 14. Hysteresis curves, envelope curve, and deflected shape for angle=50º

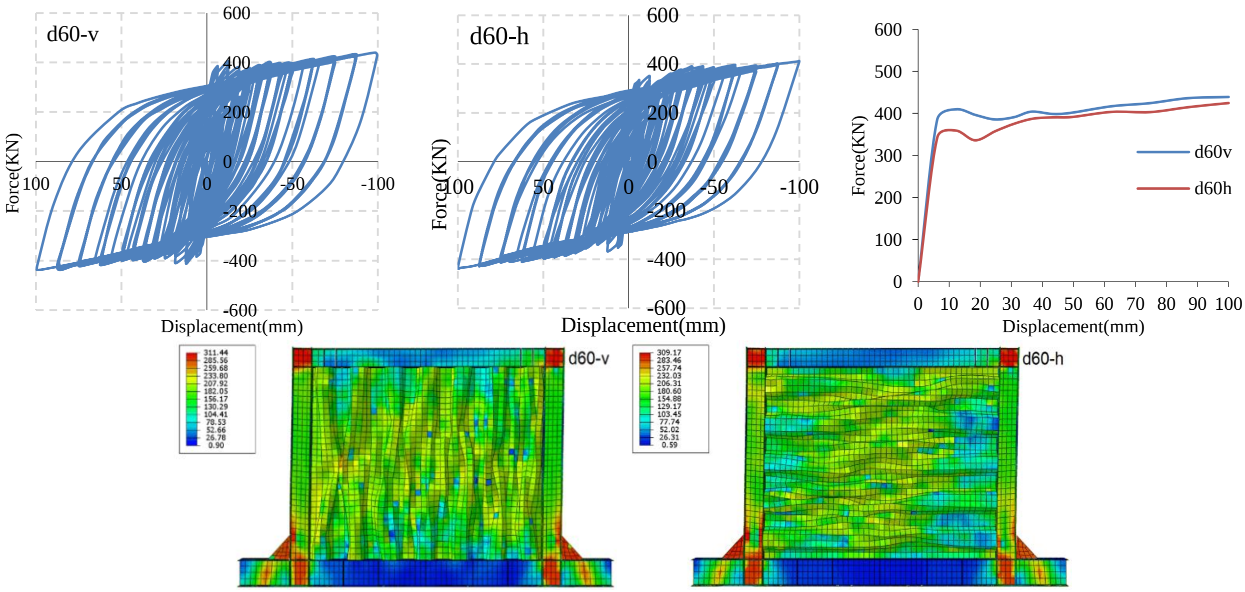

Figure 15. Hysteresis curves, envelope curve, and deflected shape for angle=60º

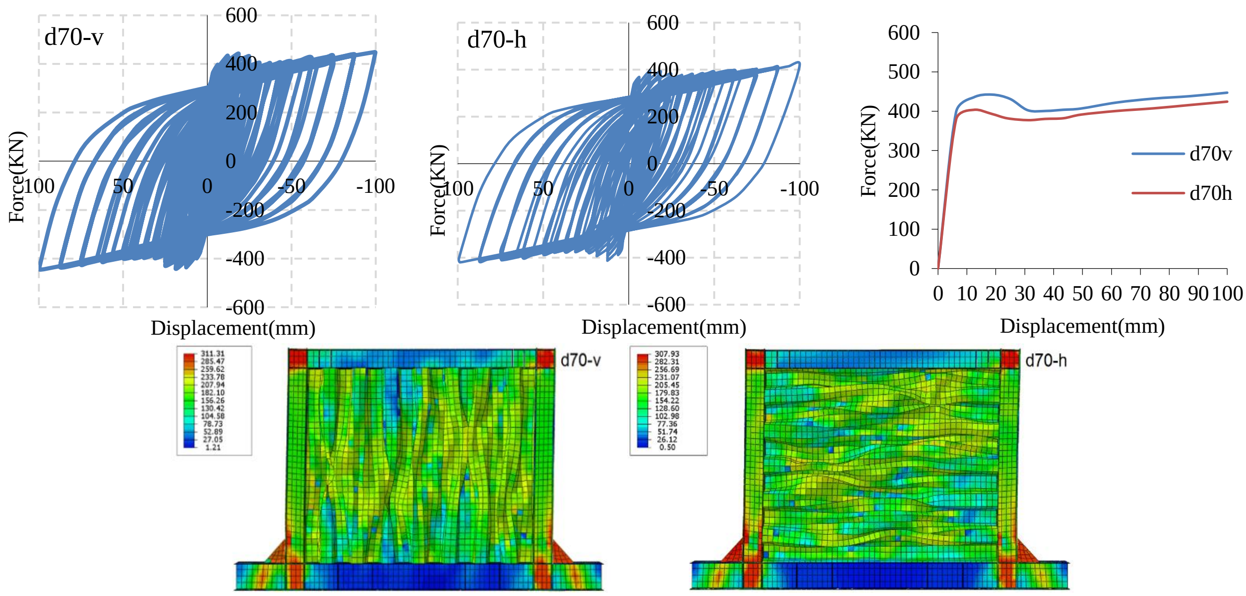

Figure 16. Hysteresis curves, envelope curve, and deflected shape for angle=70º

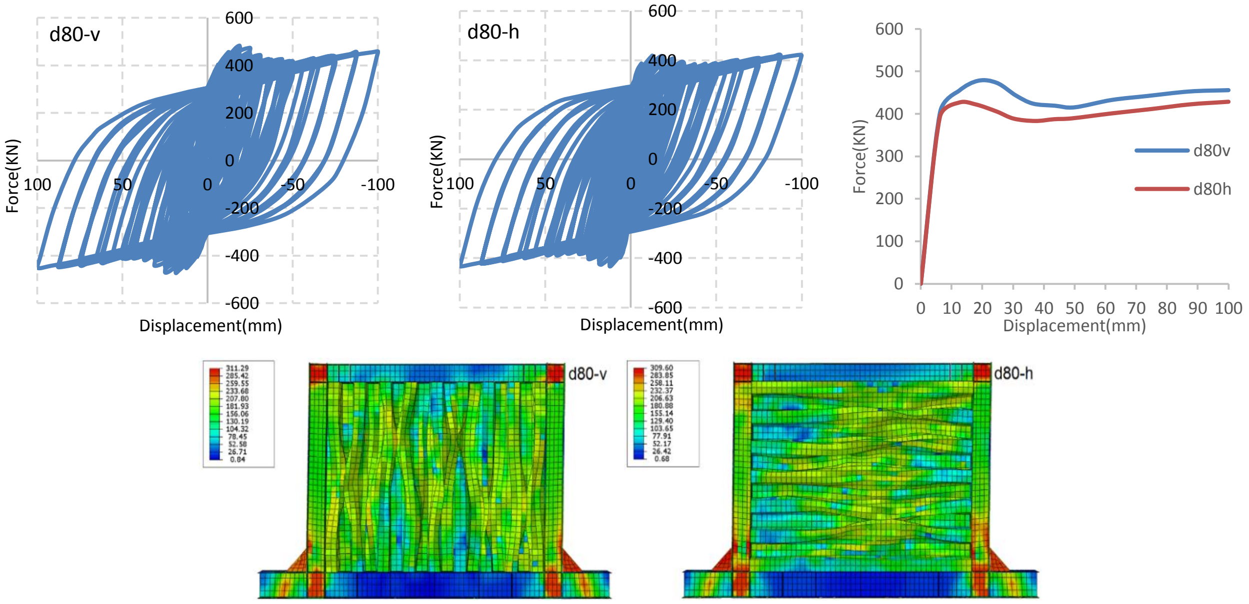

Figure 17. Hysteresis curves, envelope curve, and deflected shape for angle=80º

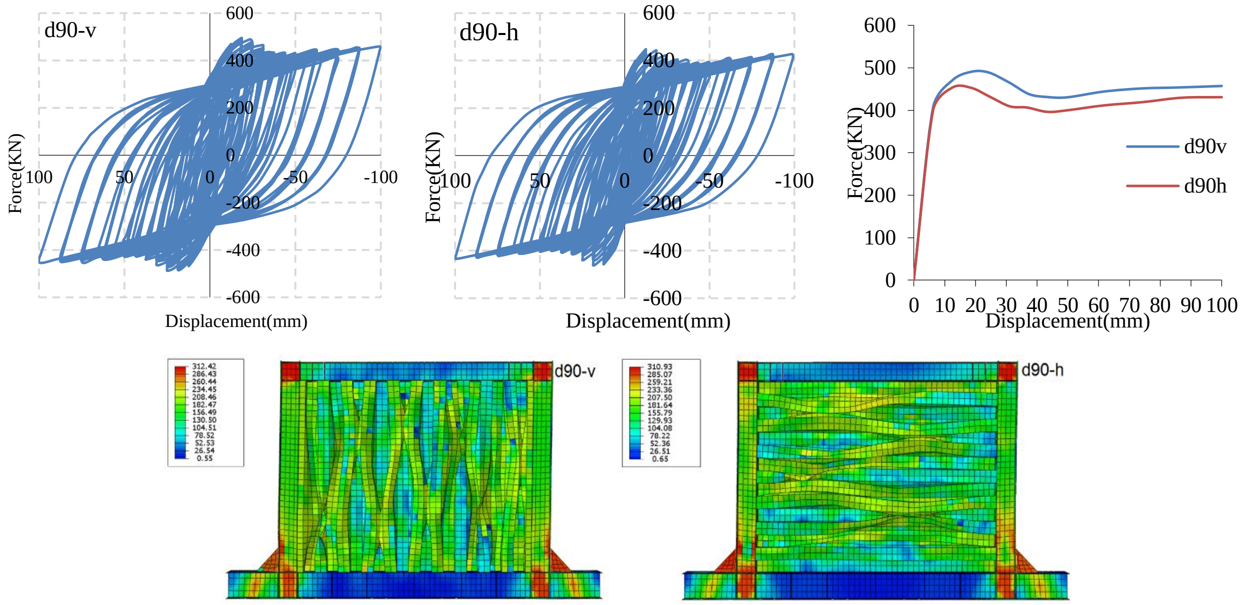

Figure 18. Hysteresis curves, envelope curve, and deflected shape for angle=90º

3.2. Strength

It is clear from Figure 19 that changing the corrugation angle could have a direct influence on the strength of the specimens. For vertical and horizontal corrugation, the influence of the corrugation angle can be divided into two stages. In the first stage, the strength is dropping significantly and it extends from 10º to 50º. The second stage covers the range between 50º and 90º. The angles show slightly effect on the strength in the second stage. The maximum strength could be obtained with the use of 10˚ angle in both directions of corrugations. This results is in agreement with the findings of Hosseinzadeh et al. [9]. The relationship between the corrugation angle and the resisting force can be explained mathematically. For equilibrium requirements, the internal force in the inclined part of the ribs (F) can be analyzed into two components: parallel to the applied load (F_x) and perpendicular to the applied load (F_y) (Figure 20). F_x is a function of cosine the corrugation angle and F_y is a function of the sine of the corrugation angle. The force responsible for lateral resistance is F_x. Mathematically, the values of cosine reduces with the increase of the angle. This means F_x is becoming smaller with the increase of the corrugation angle, which results in reducing the ultimate strength of the CSPSW.

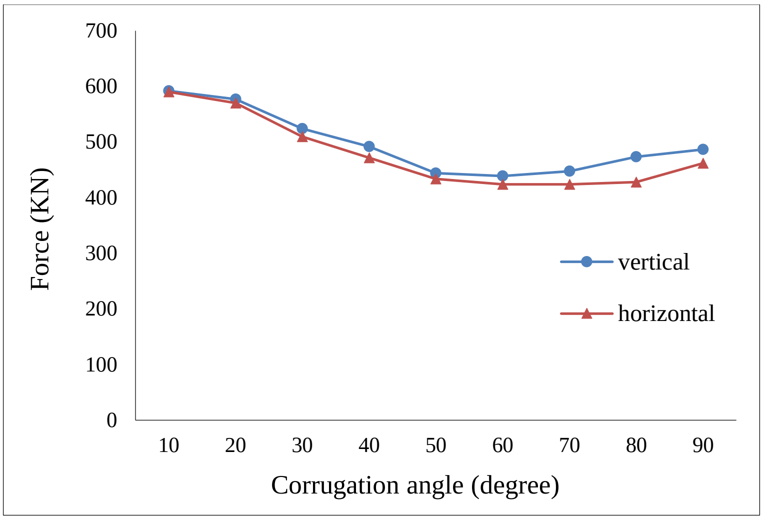

Figure 19. Influence of corrugation angle on ultimate strength

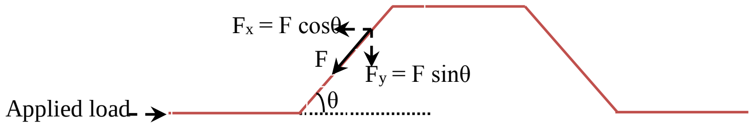

Figure 20. Representation of ribs forces

3.3. Initial Stiffness

The initial stiffness of the CSPSW with different corrugation angles for both vertical and horizontal corrugations is shown in Figure 21. The results indicate that the maximum stiffness can be obtained by using angle of 20º in horizontal corrugations and 30º in vertical corrugations. After these limits, the stiffness showed a clear reduction until 50º and then the behaviour moved to plateau for both corrugation directions. Therefore, it is recommended to use angles of 20º for horizontal corrugations and 30º for vertical corrugations to achieve the optimum performance of the CSPSW in terms of stiffness. This could be due to the fact that these angles are providing the highest rigidity to limit the displacement against the applied forces by the group action between the neighboring ribs which is related to the relationship between the angles and the forces as described previously.

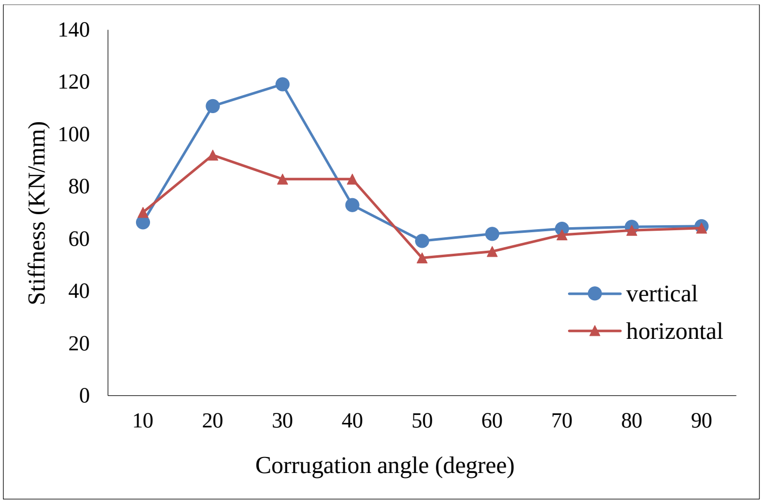

Figure 21. Influence of corrugation angle on Initial stiffness

3.4. Ductility

The ductility is the ratio of the maximum displacement to the displacement at the yield point ($\mu=\Delta_{max}/\Delta_y$). Figure 22 shows the relationship between the ductility and the corrugation angle θ. significant improvement in the ductility was recorded by increasing the angle from 10º to 30º for the vertical corrugation and from 10º to 40º for the horizontal corrugation. After these limits, the corrugation angle shows negligible effect on the ductility. The highest ductility can be obtained using a plate with vertical corrugation and angle of 30º. For angles from 30° to 40°, the cosine and sine of corrugation angles become nearly equal. This means there will be an equitable resistance force against the out of plain deformations which delays the failure appearance and allows for higher displacement in the direction of loading, which results in higher ductility. These findings do not support the previous research of Bahrebar et al. [20], in which they claimed that the corrugation angle does not have a clear effect on ductility.

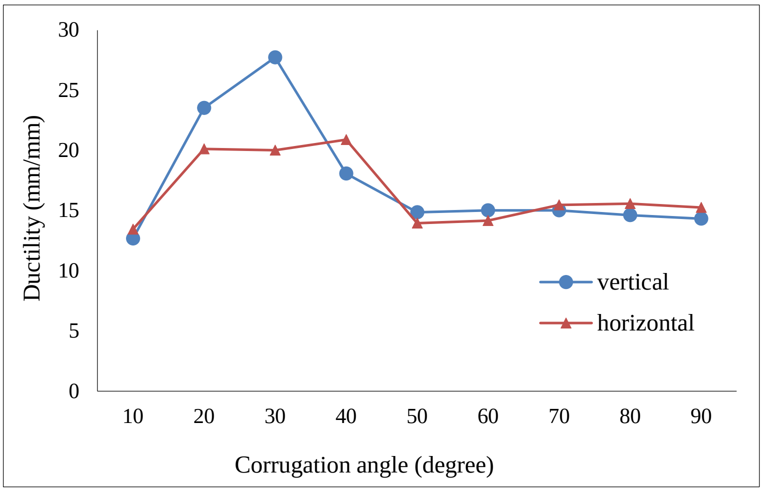

Figure 22. Influence of corrugation angle on the ductility

3.5. Energy Dissipation

The energy dissipation is considered as an important factor in seismic design. It can be calculated from the area under the cyclic curve[21]. Figure 23 presents the effect of corrugation angle on the energy dissipation for both horizontal and vertical corrugations. A reduction in the ductility was recorded with the increase of corrugation angle from 10º to 50º and there was no significant improvement with the increase of corrugation angle to more than 50˚. Therefore the angle and direction of corrugation can affect the energy dissipation marginally. The energy dissipation is mainly related to strength and displacement, since it can be calculated from the area under the cyclic curve. Referring to Figures 10 to Figure 18, the maximum displacement for all specimens was around 100 mm however, the ultimate strength was varying with the change of corrugation angle. Therefore, the difference in the ductility seems to be following the change in the ultimate strength. The vertical corrugations gives better performance than the horizontal corrugation and this agrees with what was stated by Hosseinzadeh et al. [9].

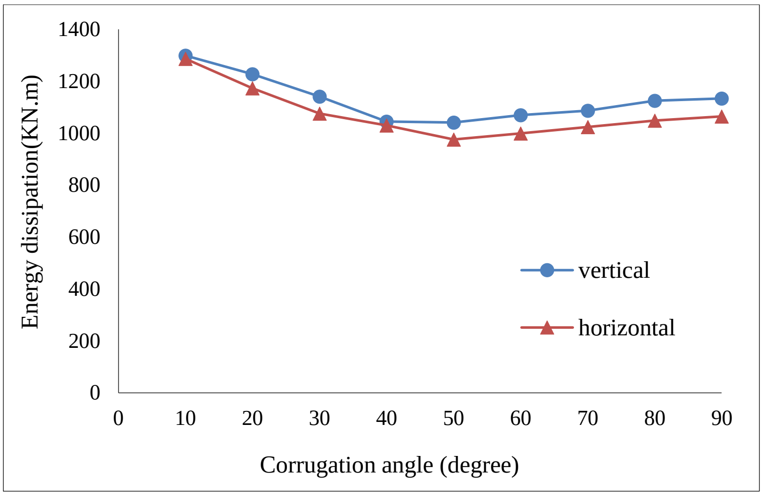

Figure 23. Influence of corrugation angle on energy dissipations

4. Conclusions

Finite element analysis was performed to evaluate the effect of corrugation angel and the direction of corrugation on the performance of CSPSW. The finite element model was validated with the available experimental data in the literature and it provided reliable results. The results reveal the following conclusions:

- For CSPSW with horizontal or vertical corrugation, the maximum strength could be obtained with the use of 10° corrugation angle.
- To achieve the maximum initial stiffness of CSPSW the corrugation angle must be 30º in vertical corrugation layout and 20º in horizontal corrugation configuration.

- Similar to initial stiffness, the highest ductility can be achieved by using corrugation angles of 30º and 20º for vertical and horizontal corrugations respectively.
- In both vertical and horizontal corrugation layouts, the increase of corrugation angle results in reducing the energy dissipation of CSPSW. So the highest energy dissipation could be obtained with the use of 10º corrugation angle.
- It is recommended to limit the maximum value of corrugations angle to 30º in vertical corrugation alignment and 20º in horizontal alignment.
- Generally, the vertical direction of corrugation provides better performance in stiffness, ductility, strength and energy dissipation compared with horizontal corrugation.

5. Conflicts of Interest

The authors declare no conflict of interest.

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