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ANALYSIS OF COMPOSITE SHEAR WALLS WITH A GAP BETWEEN REINFORCED CONCRETE WALL AND STEEL FRAME

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Abstract: In this research, nonlinear analysis of composite shear walls (CSWs) with a gap between reinforced concrete wall and steel frame is investigated under cyclic loading by the use of the finite element method (FEM) software ABAQUS. For the purpose of the verification, an experimental test is modelled and comparison of its obtained result with that of the experimental test demonstrates an inconsiderable difference between them; therefore, the reasonable accuracy of the modelling is revealed. Then, effects of different parameters on the behaviour of the CSWs are examined. Gap size between reinforced concrete wall and steel frame, reinforcement percentage, steel sections of beams and columns, and existence of reinforced concrete wall are considered as parameters. It is concluded that change of the parameters affects the ultimate strength, ductility, and energy dissipation of the system. A steel shear wall (SSW) is also modelled and compared with the CSWs. Buckling of the walls is presented as well.

Keywords: Composite Shear Wall, Steel, Reinforced Concrete, Cyclic Loading, Finite Element Method, Ultimate Strength, Energy Dissipation, Ductility

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1. INTRODUCTION

Shear wall is one of the most popular resisting systems against lateral loads. Only reinforced concrete shear wall was used up to about 30 years, but studies and researches have been done on steel shear walls (SSWs) in the past decades which led to increasing use of this system in new structures and for retrofitting of existing structures. Out-of-plane buckling of the steel plate is one of the problems associated with this type of the system which creates diagonal lines in the steel plate. Increasing and more uniform distribution of these lines result in the increased shear capacity. Using this feature is possible by the use of the reinforced concrete wall which is connected to the steel plate by shear studs (composite shear wall (CSW)). The CSWs consist of a thin steel plate layer with the reinforced concrete wall attached to one side or both sides of the steel plate using shear studs. The CSWs are divided into two types of the CSWs with and without gap between the reinforced concrete wall and steel frame. In the type of the walls without gap (traditional CSWs), concrete is destructed faster and under the intensity of lower loads. While in the type of the CSWs with gap (innovative CSWs), concrete is not under the effect of lateral loads since concrete is not involved with the steel frame and its only task is to prevent buckling of the steel plate. Hence, concrete is damaged later and under larger loads.

Various investigations have been done on the performance of the SSWs and traditional CSWs. One-storey and two-storey SSWs were tested by Takanashi et al. [1]. Kulak [2] studied the unstiffened SSWs. A cyclic-loading test on a large-scale, four-storey, single bay SSW with unstiffened panels was conducted by Driver et al. [3]. The traditional and innovative CSWs were experimentally evaluated under the cyclic loading by Zhao and Astaneh-Asl [4]. An experimental study on the behaviour of one-storey and three-storey CSWs was carried out by Arabzadeh et al. [5]. The seismic analysis of SSWs with the steel plate having opening was nonlinearly done by Bhowmick et al. [6]. CSWs consisting of a steel plate with a precast concrete panel were experimentally investigated by Guo and Yuan [7]. Titiksh and Bhatt [8] analysed four different cases of shear wall positions for G+10 storey buildings. Dastfan and Driver [9] performed a test on a large-scale SSW with partially encased composite columns and reduced beam section frame connections. Lv et al. [10] experimentally assessed four scaled one-storey single-bay SSWs with unstiffened panels. However, the study on the behaviour of the innovative CSWs is limited which has been conducted in this research.

In this paper, nonlinear analysis of CSWs with a gap between the reinforced concrete wall and steel frame is performed under the effect of cyclic loads. After modelling verification, several CSWs are analysed by considering different variables as gap sizes between reinforced concrete walls and steel frames (5.625 mm, 11.25 mm, and 22.5 mm), percentages of reinforcements in reinforced concrete walls (0.25%, 0.5%, and 1%), steel sections of beams and columns (IPE100, IPE140, and IPE180), and existence of reinforced concrete wall. Also, effects of these variables on the behaviour of the CSWs are examined.

2. EXPERIMENTAL TEST

The experimental test of a CSW which was performed under cyclic loading [5] was chosen for the verification of the nonlinear finite element modelling herein. The details of the specimen are shown in Fig. 1. Before the test, the specimen was analysed by the push-over analysis in order to assess the yield-displacement and the gap size around the wall. The gap size was considered so that no interaction could occur between the wall and the steel frame. The reaction frame, H-shape beam, lateral bracing, actuators, and specimen have been the main components of the test setup. The specimen was attached to a strong H-shape beam that was bolted to the strong floor to secure the specimen during the test. The groove welding was applied to directly connect the beam and column together. The steel plate was welded to the fish plate. Then, they were also welded to the steel frame. Therefore, the connections between the beams and columns of the steel frame have been rigid. Bottom beam of the steel frame is fixed and roof beam of the steel frame has a lateral support which prevents the out-of-plane displacement of the frame. Afterwards, the bolts and reinforcements were placed. The concrete wall was constructed using fine aggregate material and was fabricated on the steel plate. Task of shear studs (bolts) is to connect the reinforced concrete wall to the steel plate.

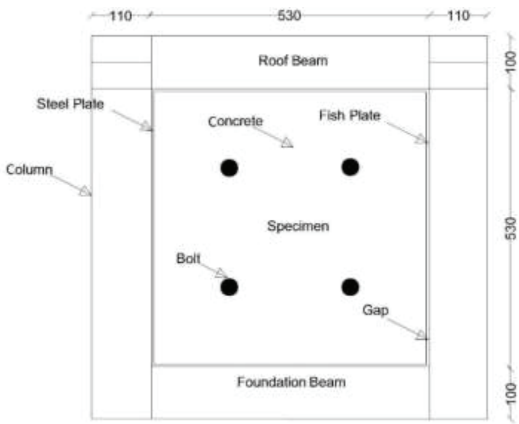

Fig. 1 Details of CSW (dimensions are in mm)

The steel columns and beams were made up of ASTM A572/50. The steel plates were ASTM A36. Table 1 summarises the material properties of the steel members used in the test. Table 2 presents the material properties of the concrete and steel bar.

Table 1 Steel properties

Section type	Yield stress, f_y (MPa)	Ultimate strength, f_u (MPa)
IPE100 beam flange	308	479
IPE100 beam web	285	446
Fish plate	297	406
Steel plate	268	415
Shear stud	900	1000

Table 2 Concrete and steel bar properties

Property	Value (MPa)
Cylinder compressive strength, f'_c	72.5
Cube compressive strength, f_{cu}	79
Yield stress, f_y	336
Ultimate strength, f_u	492
Young's modulus, E_c	21000

Specifications of the components of the experimental test have been represented in Table 3. Modulus of elasticity of the steel is 210000 MPa. Also, Poisson's ratios of the steel and concrete are 0.30 and 0.20, respectively.

Table 3 Specifications of components of experimental test

Component	Specification
Columns (mm)	2IPE100+2Pl100×5
Beams (mm)	2IPE100
Steel wall plate thickness (mm)	2
Fish plate (mm)	40×5
Number of shear studs	4
Shear stud diameter (mm)	6
Rebar diameter (mm)	3
Reinforcement ratio	1%
Concrete thickness (mm)	30
Gap size (mm)	11.25

3. MODELLING VERIFICATION

The experimental test was simulated using the FEM software ABAQUS in order to verify the modelling. All of the mentioned specifications of the tested wall have been considered in the modelling. The simulated model has the reinforced concrete wall on one side of the steel plate as in the experimental test. Modelling the constitutive behaviour of the concrete has been done by the use of a three dimensional continuum, plasticity based damage model. A steel constitutive model for the structural steel was utilised for the cyclic behaviour of the steel which has bilinear kinematic hardening behaviour in order to account for progressive hardening and softening effects. S4R element was used for the steel frame, steel plate, and fish plate. C3D8R, T3D2, and B31 elements were utilised for the concrete wall, reinforcement, and shear studs, respectively. Tie was used to define the contact surface between the components of the CSW. Combining two areas with different meshes is allowed by this constraint. The initial geometric imperfection has also been applied in the model based on the Eurocode. Embedded Region was employed for the contact surface between reinforcements and the concrete wall. Friction coefficient between the steel and concrete was considered as 0.3 [11]. The displacement method was utilised for loading [12,13]. The amount of displacement was applied to the shear wall in accordance with the loading code [14]. According to the code, the load-history of the tested specimen which is cyclic loading has been obtained and its corresponding displacement has been applied to the simulated model. The number of the load cycles of the tested specimen has been 19 with the maximum displacement of 27 mm. The support conditions of the experimental test were also simulated in the modelling.

Mesh refinement is an important step of the modelling. To determine the suitable mesh size for the model, different mesh sizes were assessed. After examining the mesh sizes and obtaining their corresponding results, the mesh size of 15 mm which finally led to more exact results was selected for the modelling. Fig. 2 illustrates the simulated model after meshing.

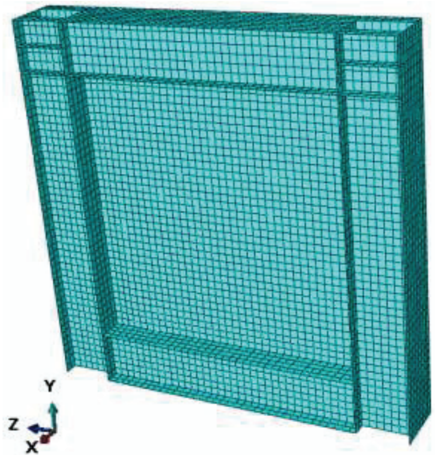

Fig. 2 A view of simulated model

To validate the numerical modelling, the load-displacement curve of the modelled CSW was depicted and compared with the result of its corresponding experimental test. As it can be observed from Fig. 3, the ultimate strength obtained from the modelling is 606 kN while it is 595 kN from the experimental test. The comparison of these two values of the ultimate strength indicates that they have a difference of only 1.8%. On the other hand, the diagrams of the specimens are very close to each other and have similar behaviour which uncover that they correlate reasonably well with each other. Therefore, because of the little difference between the ultimate strengths of the modelled and tested CSWs and the similarity in their behaviours under the applied load, it is revealed that the proposed finite element modelling is absolutely capable to predict the behaviour of the shear walls with a very good accuracy herein.

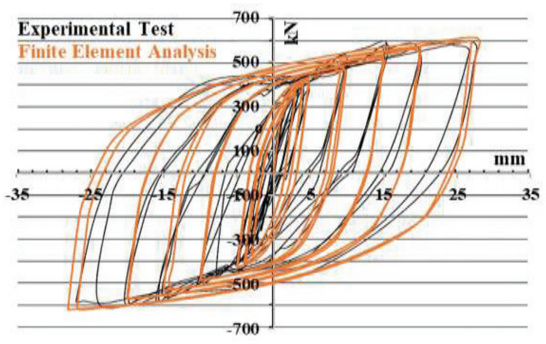

Fig. 3 Comparison of hysteresis curves of numerical model and experimental test specimen

4. NUMERICAL STUDY

Because the proposed finite element modelling of this research was verified, the method was used for the nonlinear analyses of developed CSWs and SSW with the same dimensions. Models designations, specifications of the models components, and obtained ultimate strengths are listed in Table 4.

5. COMPARISONS OF RESULTS AND DISCUSSIONS

Various parameters were chosen to study their effects on the behaviour of shear walls using ABAQUS which are presented in the following:

5.1 EFFECT OF GAP SIZE BETWEEN REINFORCED CONCRETE WALL AND STEEL FRAME

Three different gap sizes (5.625 mm, 11.25 mm, and 22.5 mm) were considered in the nonlinear analyses of the CSWs in order to investigate the effect of the gap size on their performance. According to the obtained results in Table 4 and Fig. 4, increasing the gap size of the CSWs from

Table 4 Specifications of numerical models

No.	Name	Reinforced concrete wall thickness (mm)	Steel plate thickness (mm)	Gap size (mm)	Reinforcement %	Beam section (mm)	Column section (mm)	P_{max} (kN)
1	CSW-30-2-11-1-100-100	30	2	11.25	1	IPE100	IPE100	606
2	CSW-30-2-5-1-100-100	30	2	5.625	1	IPE100	IPE100	692
3	CSW-30-2-22-1-100-100	30	2	22.5	1	IPE100	IPE100	480
4	CSW-30-2-11-0.5-100-100	30	2	11.25	0.5	IPE100	IPE100	596
5	CSW-30-2-11-0.25-100-100	30	2	11.25	0.25	IPE100	IPE100	592
6	CSW-30-2-11-1-140-140	30	2	11.25	1	IPE140	IPE140	1151
7	CSW-30-2-11-1-180-180	30	2	11.25	1	IPE180	IPE180	1213
8	CSW-30-2-11-1-100-140	30	2	11.25	1	IPE100	IPE140	1114
9	CSW-30-2-11-1-140-100	30	2	11.25	1	IPE140	IPE100	845
10	CSW-30-4-5-0.25-100-140	30	4	5.625	0.25	IPE100	IPE140	1117
11	CSW2-30-4-5-0.25-100-140	30 (both sides)	4	5.625	0.25	IPE100	IPE140	1140
12	SSW	-	4	-	-	IPE100	IPE140	892

5.625 mm (CSW-30-2-5-1-100-100) to 11.25 mm (CSW-30-2-11-1-100-100) and then 22.5 mm (CSW-30-2-22-1-100-100) respectively reduces the ultimate strength from 692 kN to 606 kN and 480 kN which elaborates respective reductions of the ultimate strengths as 12.4% and 20.8%. Also, the figure indicates that increasing the gap size decreases the ultimate strength and the areas of the load-displacement hysteresis curves. Therefore, the enhancement of the gap size reduces the ultimate strength, ductility, and energy dissipation of the CSWs. The reason is that the considered gap between the reinforced concrete wall and the steel frame reduces the damages which may occur in the concrete and delays the buckling of the steel plate. Since the steel plate has the main role in carrying the applied load, utilising the minimum gap size of 5.625 mm can be adequate while more increase of the gap size brings less contribution of the wall to withstanding the load and finally results in the weakness of the CSWs' performance.

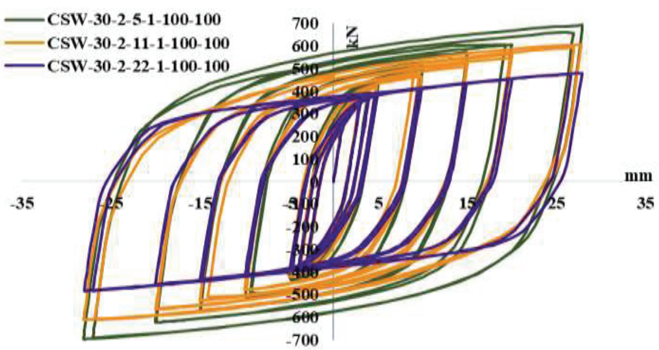

Fig. 4 Effect of gap size between reinforced concrete wall and steel frame

5.2 Effect of reinforcement percentage

To evaluate the effect of the reinforcement percentage, two other reinforcement percentages of 0.25% and 0.50% have also been adopted in the analyses of the CSWs, in addition to the reinforcement percentage of 1%. Table 4 and Fig. 5 illustrate that as the reinforcement percentage enhances from 0.25% in CSW-30-2-11-0.25-100-100 to 0.5% in CSW-30-2-11-0.5-100-100 and 1 % in CSW-30-2-11-1-100-100, the ultimate strengths of the CSWs are respectively improved about 1% and 1.7%. Moreover, comparison of obtained results from the analyses of the CSWs with different reinforcement percentages in Fig. 5 demonstrates that the models have similar behaviour and the areas of their load-displacement hysteresis curves do not significantly change with increasing the reinforcement percentage. As a consequence, the enhancement of the reinforcement percentage does not considerably affect the ultimate strength, ductility, and energy dissipation of the CSWs. This is because of the point that the reinforcements mainly strengthen the concrete, on the other hand, the major task of the reinforced concrete is to stiffen the steel plate and prevent its buckling. Therefore, the reinforcements of the concrete do not directly contribute to carry the applied load.

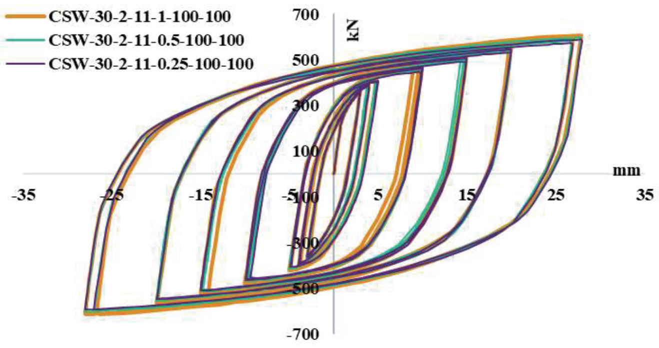

Fig. 5 Effect of reinforcement percentage

5.3 Effect of steel frame section

Not only IPE100 but also IPE140 and IPE180 have been considered for the steel frame of the CSWs to assess their effect. Enhancing the steel frame section in CSW-30-2-11-1-100-100 from IPE100 to IPE140 in CSW-30-2-11-1-140-140 and IPE180 in CSW-30-2-11-1-180-180 increases their ultimate strengths as 89.9% and 5.4%, respectively (Table 4). Therefore, change of the beam and column sections increases the ultimate strength with its corresponding enhancement of the structure weight. However, the section increase is optimum up to IPE140 and enhancing the steel frame section to IPE180 does not have very much effect on the structure ultimate strength and it significantly increases the structure weight which will not be cost-effective. Moreover, obtained results illustrate that the areas of the load-displacement hysteresis curves are increased with the enhancement of the steel frame section which demonstrates that the increase of the steel frame section enhances the ductility and energy dissipation (Fig. 6). This considerable effect of enhancing size of the steel frame section on the performance of the CSWs is because of the remarkable contributing role of the steel frame in bearing the load.

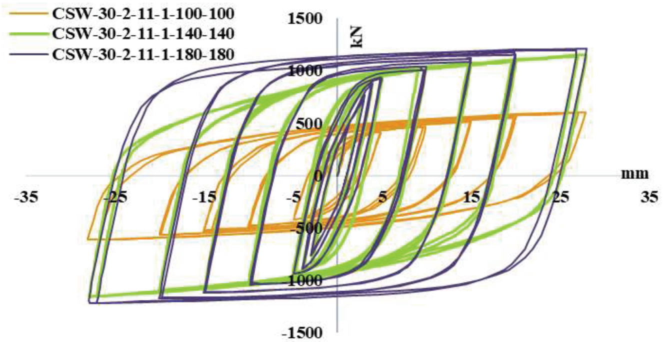

Fig. 6 Effect of steel frame section

In order to investigate the role of the steel frame beam and column, the effect of each of them was thereafter studied. Since IPE180 section is not optimum, it is not considered herein and the numerical study has been carried out on IPE100 and IPE140 sections. In accordance with the achieved results in Table 4, the change of the column section from IPE 100 to IPE140 increases the ultimate strength from 606 kN (CSW-30-2-11-1-100-100) to 1114 kN (CSW-30-2-11-1-100-140), an enhancement of 83.8%. However, enhancing the beam section from IPE100 (CSW-30-2-11-1-100-100) to IPE140 in CSW-30-2-11-1-140-100 improves the ultimate strength from 606 kN to 845 kN, an imptovement of 39.4%. Accordingly, it uncovers that increasing the column section of the steel frame is more effective on the ultimate strength, ductility, and energy dissipation compared with enhancing the beam section (Fig. 7).

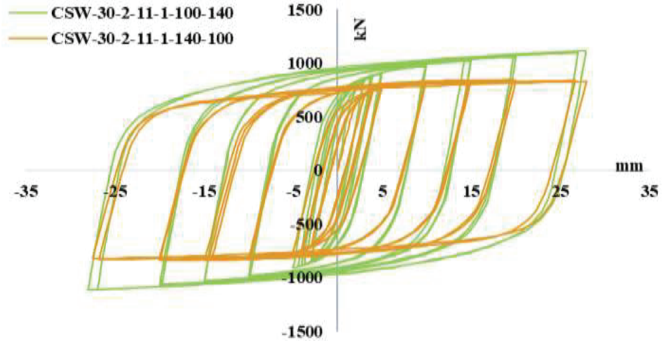

Fig. 7 Effect of beam and column sections

5.4 Effect of existence of reinforced concrete wall

In this part, two CSWs with reinforced concrete wall on one side and also both sides of the steel plate have been modelled. Moreover, a CSW without reinforced concrete wall (SSW) has been simulated.

Table 4 indicates that the ultimate strength of the SSW (without reinforced concrete wall) as 892 kN has been increased to 1117 kN and 1140 kN respectively by the use of the reinforced concrete wall on one side (CSW-30-4-5-0.25-100-140) and on both sides of the steel plate (CSW2-30-4-5-0.25-100-140) which witnesses the respective ultimate strengths improvements of 25.2% and 2.1%. Meanwhile, comparing the obtained curves (Fig. 8) reveals that the existence of the reinforced concrete wall on both sides of the steel plate does not significantly influence the ultimate strength, ductility, and energy dissipation of the CSWs and the reinforced concrete wall on one side of the steel plate suffices to achieve the optimum performance of the shear walls. Because as it was mentioned earlier, the concrete mainly tries to prevent the buckling of the steel plate and does not considerably contribute to carry the load, therefore, the existence of the concrete on one side of the shear wall is adequate.

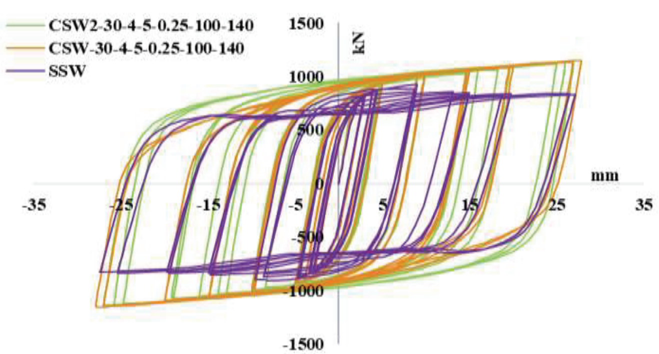

Fig. 8 Effect of existence of reinforced concrete wall

Fig. 9 shows that the steel plate of the SSW had overall buckling. With regard to the reinforced concrete wall on the steel plate in the CSWs, the figure illustrates that as the load increased, local buckling of the steel plate occurred and the steel plate has got a little out-of-plane displacement.

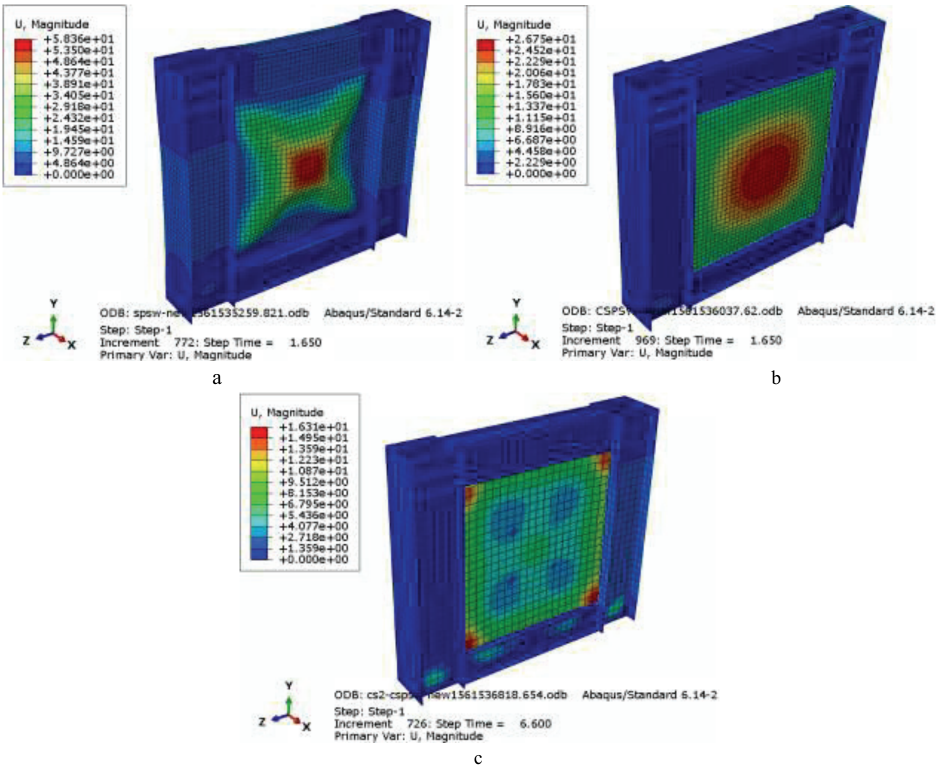

Fig. 9 Buckling of SSW and CSWs: (a) SSW, (b) CSW-30-4-5-0.25-100-140, (c) CSW2-30-4-5-0.25-100-140

6. Conclusions

In this paper, the CSWs with a gap between the reinforced concrete wall and steel frame were investigated under cyclic loads. Obtained result from the modelling was compared with that of the experimental test which showed a very good accuracy of the proposed finite element modelling. Then, effects of various parameters on the behaviour of the shear walls were assessed. Results uncovered that enhancing the gap size from a certain value reduces the ductility, energy dissipation, and ultimate strength. Also, change of the reinforcement percentage does not remarkably influence the ultimate strength, energy dissipation, and ductility. In addition, increasing the beam and column sections of the steel frame improves the ultimate strength, energy dissipation, and ductility, but role of the column of the steel frame in the enhancement of the CSWs' performance is much more than the beam of the steel frame. Meanwhile, the existence of the reinforced concrete wall on one side of the steel plate can be sufficient to obtain the optimum performance of the shear walls.

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LIST OF FIGURES AND TABLES:

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