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Hysteretic Assessment of Steel-Concrete Composite Shear Walls

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Abstract: This paper focuses on the hysteretic assessment of steel-concrete composite shear walls with reinforced concrete on one side of the steel plate. Finite element software ABAQUS is utilised to conduct this research. An experimental test on a composite shear wall is simulated to do the verification of the modelling. Then, modelling result is compared with the experimental test result which shows an insignificant difference between them and therefore uncovers the accuracy of the modelling. Thereafter, different parameters are considered to investigate their effects on the response of the walls. Thickness of reinforced concrete, steel plate thickness, and number of shear studs are studied as parameters. It is concluded that changing reinforced concrete thickness and number of shear studs do not considerably affect the ultimate load capacity, ductility, and energy dissipation of the walls. However, increasing the steel plate thickness enhances the ultimate load capacity, ductility, and energy dissipation. In addition, out-of-plane displacement of the walls is evaluated.

Keywords: shear wall, cyclic loading, ultimate load capacity, ductility, energy dissipation.

I. INTRODUCTION

Up to about 30 years, reinforced concrete shear wall was applied to withstand lateral loads, but investigations have then been conducted on steel shear walls leading to the increasing usage of this system. Steel shear walls have a problem during resisting lateral loads which is the out-of-plane buckling of the steel plate. This problem makes diagonal lines in the steel plate. However, more uniform distribution of these diagonal lines leads to enhancing shear capacity of the walls. This problem of the steel shear walls can be solved by the use of reinforced concrete connected to the steel plate by shear studs, i.e. steel-concrete composite shear wall (SCCSW).
Reinforced concrete can be connected to one side or both sides of the steel plate by shear studs. There are 2 types of the SCCSWs which are with and without gap between the reinforced concrete and steel frame. In the type of the SCCSWs without gap that are traditional, concrete is damaged faster and under lower loads. However, in the type of the SCCSWs with gap which are innovative, concrete is destructed under larger loads because concrete is not subjected to lateral loads since concrete is not involved with its surrounding beam and column. Concrete delays the buckling of the steel plate which is its only task.
Tests on one-story and two-story specimens of SCCSWs were performed by Takanashi et al. [1]. Timler and Kulak [2] tested steel shear walls under uniform and cyclic loading. Nakashima et al. [3] carried out tests on steel shear walls to investigate their behaviour. Zhao and Astaneh-Asl [4] experimentally tested 2 SCCSW specimens, one for the traditional system, while the other one for the innovative system. Rahai and Hatami [5] evaluated variables of the SCCSWs in a numerical and experimental investigation. Behaviour of one-story and three-story specimens was experimentally investigated under cyclic loading by Arabzadeh et al. [6]. Another type of SCCSW composed of two steel plates and sandwich concrete was assessed by Nie et al. [7]. The effectiveness of reinforced concrete shear walls in medium rise buildings was studied by Govalkar et al. [8]. Guo and Yuan [9] presented a type of shear wall which was assembled by the use of a steel plate and a precast concrete panel. A review of methods and techniques used in retrofitting reinforced concrete shear walls was done by Mahadik and Bhagat [10]. The shear strength of cold-formed steel framed wall assemblies with corrugated sheet steel sheathing was experimentally carried out by Yu and Vora [11]. Dastfan and Driver [12] tested steel plate shear walls with partially encased composite columns and reduced beam section frame connections to evaluate the behaviour of the system. Performance of various shapes of shear walls was investigated by Gupta and Bano [13].

The current paper deals with the hysteretic assessment of innovative SCCSWs with reinforced concrete on one side of the steel plate. Finite element software ABAQUS is applied in this study. An experimental test of a SCCSW is modelled in order for the verification of the modelling. Then, the result obtained from the modelling is compared with that of the experimental test which demonstrates that there is an inconsiderable difference between them. As a consequence, the verification of the modelling is revealed. Thereafter, parametric studies on SCCSWs are done with various parameters. The parameters are thicknesses of reinforced concrete (30 mm, 60 mm, and 100 mm), thicknesses of steel plates (2 mm, 4 mm, and 8 mm), and number of shear studs (4, 9, and 16).

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Moreover, effects of these parameters on the response of the SCCSWs are evaluated. In addition, out-of-plane displacement of the walls is discussed.

II. MODELLING

A. *Experimental Testing*

In order to do the verification of the modelling, an experimental testing of a SCCSW [6] was chosen in which the reinforced concrete is connected to one side of the steel plate by shear studs. A view of the tested and simulated SCCSW is presented in Fig. 1.

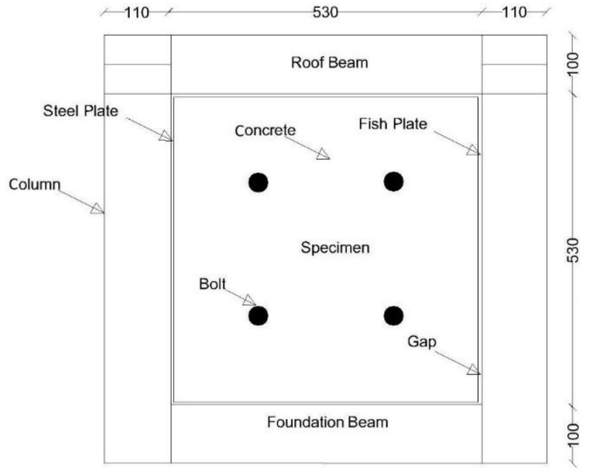


Fig. 1 A view of tested and simulated SCCSW (dimensions are in mm)

B. *Material Modelling*

Material modelling of steel and concrete is a fundamental part of numerical modelling [14,15,16]. A three dimensional continuum, plasticity based damage model was used for modelling the constitutive behaviour of the concrete. Modelling the concrete as solid can efficiently be carried out by the concrete damaged plasticity model. In order to calculate the compression strain curve of the concrete, the following formula [17] has been used.

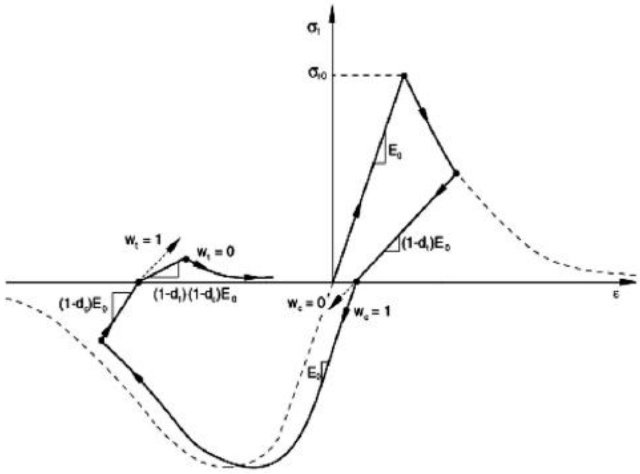
$$\sigma_c = \frac{f'_c \gamma (\frac{\varepsilon_c}{\varepsilon'_c})}{\gamma - 1 + (\frac{\varepsilon_c}{\varepsilon'_c})^{\gamma}}$$

where σ_c, ε_c, and f'_c are compressive stress, strain, and cylinder compressive strength of the concrete respectively, and ε'_c is strain corresponding to f'_c, and γ is given by:

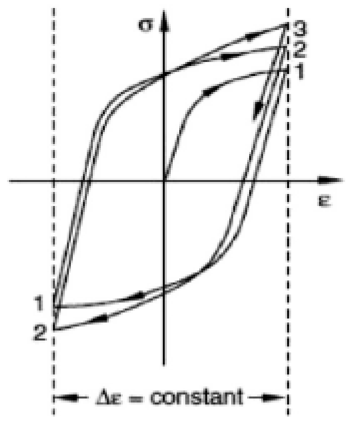
$$\gamma = [\frac{f'_c}{32.4}]^3 + 1.55$$

The strain ε'_c was considered as 0.002. The stress–strain behaviour of the compressive concrete was assumed linearly elastic up to $0.4f'_c$. To define the stress–strain relationship of the concrete in modelling, the plastic strain was considered beyond this region. Concrete in tension was assumed a linear–elastic material until the uniaxial tensile stress at which cracks in the concrete occurred. The cyclic behaviour of the concrete is illustrated in Fig. 2-a. A steel constitutive model was utilised for the cyclic behaviour of the steel. Fig. 2-b indicates the cyclic response of the steel under strain-controlled loading schemes. The steel is considered to have bilinear kinematic hardening behaviour to take into account progressive hardening and softening effects [18].

Table 1 lists the material properties of each steel member utilised in the test. Table 2 summarises the material properties of the reinforced concrete.



a. Concrete



b. Steel

Fig. 2 Cyclic behaviour

C. *Verification of Modelling*

Specifications should be introduced in the first stage to simulate the SCCSW under cyclic loading. System of the SCCSW includes steel frame (beams and columns), steel plate, fish plate, concrete, reinforcement, and shear studs (bolts).

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 Reinforced concrete 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

Bottom steel beam of the frame has fixed conditions and roof steel beam of the frame has a lateral support preventing the out-of-plane displacement of the frame.

At first, the experimental test was simulated in order to do the verification of the modelling. Features of the components of the experimental test have been presented in Table 3. The model has the reinforced concrete on one side of the steel plate as in the experimental test. 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. S4R shell element was utilised for the steel frame, steel plate, and fish plate. This element is a 4-noded element in which each node has 6 degrees of freedom. C3D8R, T3D2, and B31 elements were applied for the concrete, reinforcement, and shear studs, respectively. C3D8R is an 8-noded solid element in which each node has 3 degrees of freedom. T3D2 is a 2-noded truss element with 3 degrees of freedom on each node. B31 is a three dimensional first degree element with 2 nodes. This element has 6 degrees of freedom on each node. Tie has been used for the contact surface between components of the SCCSW. Combining two areas with different meshes is allowed by this constraint. Embedded Region was utilised for the contact surface between reinforcements and the concrete. The displacement method has been used for loading [14,15,16]. In accordance with the loading code [19], the amount of displacement was applied to the wall. The boundary conditions of the experimental test were also considered in the modelling. In order to obtain the suitable mesh size for the model, different mesh sizes were examined which finally led to more accurate results. Fig. 3 illustrates mesh of the simulated model. By comparing the hysteresis curve of the numerical model with that of the experimental test, it is concluded that the wall can bear the maximum force of 595 kN in the experimental test and this force is 606 kN in the numerical model. This issue shows that the difference between the result of the numerical model and that of the experimental test is only 1.8% (Fig. 4). Moreover, by the comparison of the curves obtained from the modelling and experimental test it can be observed that the curves are similar with each other from the behavioural point of view. As a consequence, the inconsiderable difference between the results and also their behavioural similarities uncover that they are in a very good agreement with each other. Therefore, the finite element modelling is perfectly capable to predict the response of the walls accurately.

III. FINITE ELEMENT ANALYSIS

After the verification of the nonlinear finite element modelling was done, further analyses of SCCSWs were conducted with the same dimensions considering different parameters. Table 4 lists features of the models and obtained ultimate load capacities. As can be seen from the table, numbers following SCCSW respectively present reinforced

Table 3 Features of components of experimental test

Component	Feature
Columns (mm)	2IPE100+2Pl100×5
Beams (mm)	2IPE100
Steel 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 (mm)	11.25

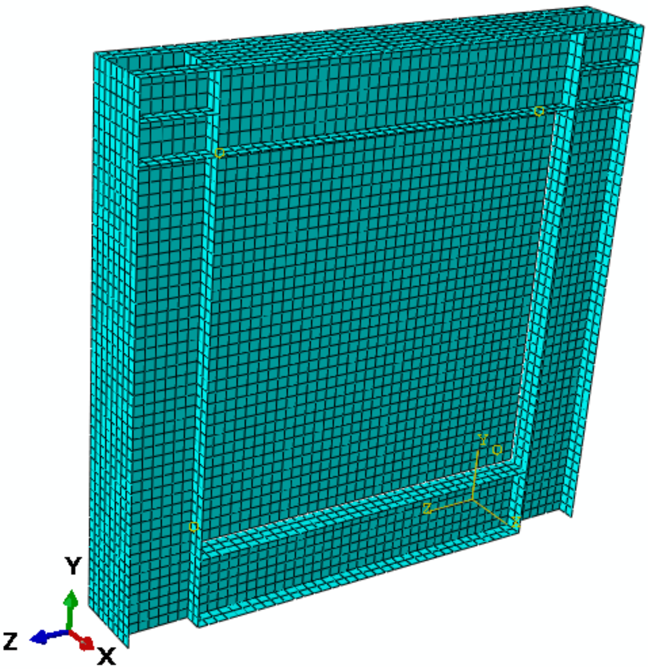


Fig. 3 Mesh of simulated model

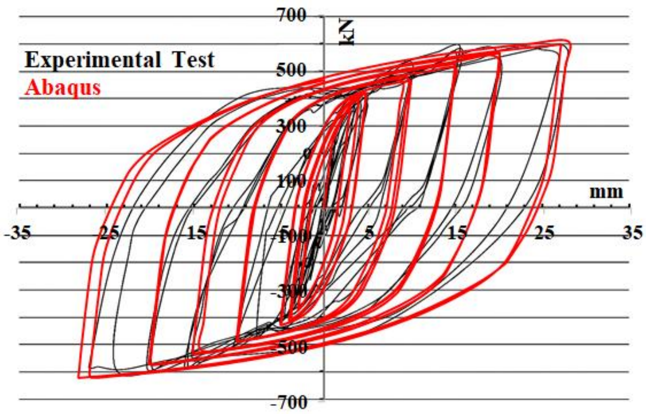


Fig. 4 Comparison of hysteresis curves of finite element model and experimental test (verification)

concrete thickness, steel plate thickness, and number of shear studs. Material properties of the components of the walls have been taken as mentioned in the previous sections.

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Table 4 Features of analysed SCCSWs

No.	Name	Reinforced concrete thickness (mm)	Steel plate thickness (mm)	Shear studs number	F_{max} (kN)
1	SCCSW-30-2-4	30	2	4	606
2	SCCSW-60-2-4	60	2	4	637
3	SCCSW-100-2-4	100	2	4	647
4	SCCSW-30-4-4	30	4	4	800
5	SCCSW-30-8-4	30	8	4	889
6	SCCSW-30-2-9	30	2	9	609
7	SCCSW-30-2-16	30	2	16	609

IV. RESULTS AND DISCUSSIONS

Obtained results from the analyses of the SCCSWs are depicted as hysteresis curves. Effects of each parameter on the ultimate load capacity, energy dissipation, and ductility of the walls are assessed.

A. *Effect of Reinforced Concrete Thickness*

To study the effect of the reinforced concrete thickness on the response of SCCSWs, reinforced concrete thicknesses of 30 mm, 60 mm, and 100 mm were considered for the models.

Results in Table 4 demonstrate that the ultimate load capacity is enhanced 5.1% by increasing the thickness of the reinforced concrete from 30 mm (SCCSW-30-2-4) to 60 mm (SCCSW-60-2-4). Also, the comparison of enhancing reinforced concrete thickness from 60 mm (SCCSW-60-2-4) to 100 mm

(SCCSW-100-2-4) indicates 1.6% increase in the ultimate load capacity of the wall. Consequently, the obtained results revealed that there is not much difference in the ultimate load capacity increase of the SCCSWs with the enhancement of the reinforced concrete thickness.

The results of comparing hysteresis curves of the models are also shown in Fig. 5. By comparing the curves, it is found that they have slight differences and similar behaviour. Due to the fact that the areas of the curves are almost identical in all models, it can be concluded that the increase of the reinforced concrete thickness has limited effect on the ductility and energy dissipation of the SCCSWs.

B. *Effect of Steel Plate Thickness*

Thickness of the steel plate has been studied as one of the parameters for SCCSWs. Accordingly, the SCCSWs with thicknesses of the steel plates as 2 mm, 4 mm, and 8 mm have been analysed.

The results represent that increasing the steel plate thickness from 2 mm (SCCSW-30-2-4) to 4 mm (SCCSW-30-4-4) improves the ultimate load capacity of the SCCSWs for 32% (Table 4). Also, the weight of the steel plate is enhanced 4.41 kg for this thickness increase. With doubling the steel plate thickness from 4 mm (SCCSW-30-4-4) to 8 mm (SCCSW-30-8-4), it is observed that the ultimate load capacity of the wall is enhanced 11.1% while the steel plate is weighed 8.82 kg in which the effect of thickness increase on the ultimate load capacity of the wall has been reduced compared with the previous one (thickness increase from 2 mm to 4 mm). Further, the enhancement of the steel plate thickness from 4 mm to 8 mm increases the weight of the steel plate a lot which leads to the enhancement of the total weight of the wall.

Fig. 6 illustrates that the enhancement of the steel plate thickness in the SCCSWs enhances the areas of their load-displacement hysteresis curves. Accordingly, it can be concluded that the increase of the steel plate thickness results in the improvement of the ductility and energy dissipation of the walls. With respect to the specific role of the steel plate in the SCCSWs, the results uncover that the steel plate strength increases with the thickness enhancement and the steel plate buckles under larger loads which leads to the increase of the ultimate load capacity of the whole wall. Also, it can be concluded that the ultimate load capacity of the SCCSW reaches its optimum value by the use of the steel plate thickness of 4 mm, and more increase of the steel plate thickness has limited effect on the enhancement of the ultimate load capacity of the wall and mostly increases its weight.

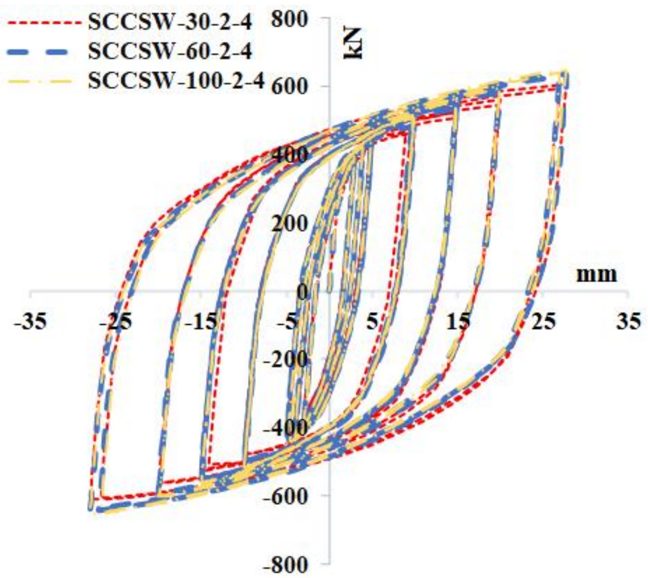

Fig. 5 Comparison of hysteresis curves (effect of reinforced concrete thickness)

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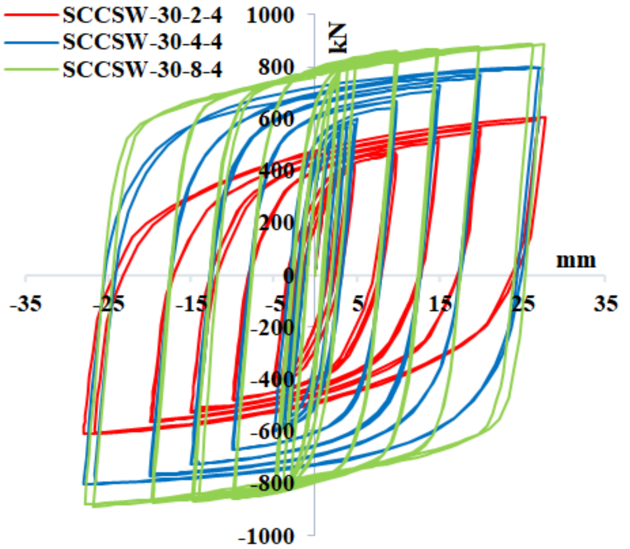


Fig. 6 Comparison of hysteresis curves (effect of steel plate thickness)

C. *Effect of Number of Shear Studs*

Shear studs as connectors of the concrete to the steel plate are one of fundamental components of the SCCSWs. Hence, number of shear studs is considered as 4, 9, and 16 in this study. Results obtained from the analyses indicate that the increase of the shear studs number from 4 (SCCSW-30-2-4) to 9 (SCCSW-30-2-9) improves the ultimate load capacity for 0.5%, as can be observed from Table 4. Also, increasing shear studs number from 9 (SCCSW-30-2-9) to 16 (SCCSW-30-2-16) has no change on the ultimate load capacity of the wall. Therefore, the increase of the shear studs number (reducing their space) does not have considerable effect on the ultimate load capacity of the SCCSWs. As the concrete has no important role in the ultimate load and only prevents buckling of the steel plate, minimum number of shear studs can be sufficient. Also, hysteresis curves of the models in Fig. 7 coincide with each other and the areas of the curves do not change with the increase of the shear studs number. Consequently, change of the shear studs number has no significant effect on the ductility and energy dissipation of the SCCSWs.

D. Out-Of-Plane Displacement of SCCSWs

In this section, out-of-plane displacement of the SCCSWs is investigated under cyclic loading. Fig. 8 represents the out-of-plane displacement of the models. As can be seen from the figure, local buckling gradually occurred in the steel plate of the SCCSWs and the steel plate had a little out-of-plane displacement. This out-of-plane displacement has been a little on edges of the steel plate and it increased as moved towards the centre of the steel plate. The maximum displacement has occurred in the centre of the wall.

V. CONCLUSIONS

In the current research, hysteretic assessment of the innovative SCCSWs were carried out. Finite element software ABAQUS was applied for the nonlinear analyses of the SCCSWs. In order to do the modelling verification, the experimental test of a SCCSW was modelled using the finite element method. Accuracy of the modelling was revealed by comparison of the obtained result from the modelling with that of the experimental test. Then, effects of different variables on the response of the walls were assessed.

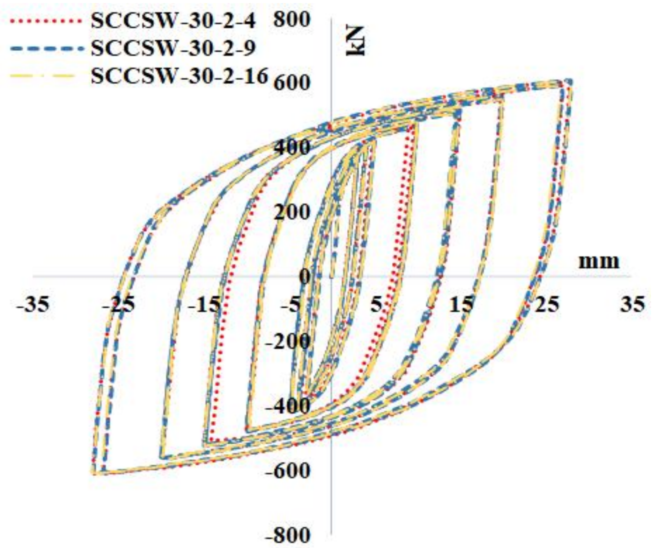
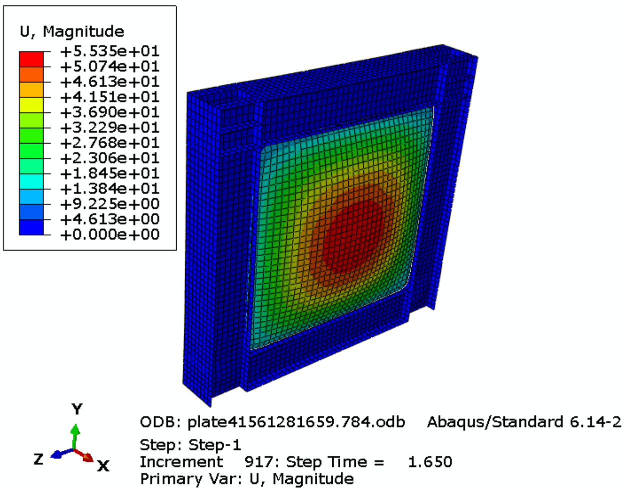
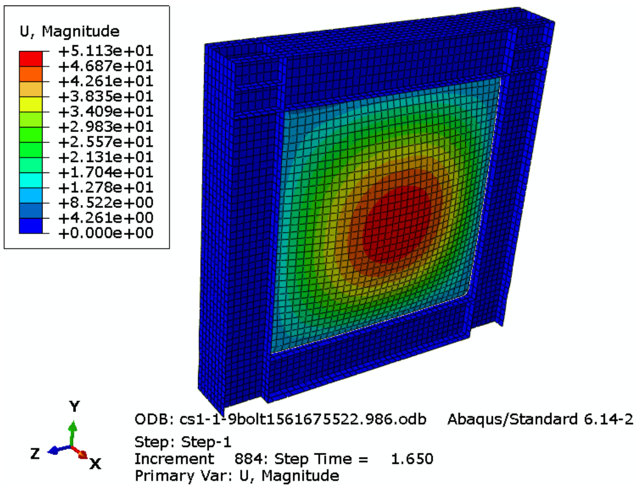


Fig. 7 Comparison of hysteresis curves (effect of shear studs number)



SCCSW-30-4-4



SCCSW-30-2-4

Fig. 8 Out-of-plane displacement of SCCSWs

Studied parameters were thickness of reinforced concrete, thickness of steel plate, and number of shear studs. Results uncovered that increasing the thickness of the reinforced concrete and shear studs number does not have a significant effect on the ultimate load capacity, energy dissipation, and ductility of the walls, and the concrete only has a lateral stiffening role for the steel plate in which the minimum thickness would suffice. However, the enhancement of the steel plate thickness improves the ultimate load capacity, energy dissipation, and ductility of the walls. Out-of-plane displacement of the walls was presented as well.

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