Analysis of the influencing parameters of double steel-plate composite shear wall

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Abstract. The double steel plate concrete composite shear walls are widely used in nuclear power structures due to good bearing capacity, deformation capacity and radiation resistance. The shear walls of nuclear power structures are totally different with that in the civil buildings, which have the characteristics of small shear span to depth ratio and large thickness. On the basis of summarizing and analysing the test results of double steel plate composite shear wall, finite element models were established to verify the validity of the simulated results. Moreover, the influence of steel ratio, axial compression ratio and shear span to depth ratio on the bearing capacity of composite shear wall was studied. The results showed that the composite shear wall has good mechanical performance. Steel ratio and shear span to depth ratio had remarkable influence on the bearing capacity of the composite shear walls.

1. Introduction
Steel-plate composite (SC) reinforced concrete shear wall is a popular kind of new structure system. Generally, a SC shear wall has two steel plates connected with tie bars and concrete infilled, and shear studs are often welded on the steel plates to avoid large slip deformation between steel plates and concrete core. SC wall shows good bearing capacity in seismic design and efficient construction since steel plates also act as formwork [1]. SC walls are used in the latest nuclear power plants [2] that have clear features of small shear span to depth ratio (also called shear span ratio) and large thickness [3-4].

Many scholars studied seismic behavior of SC shear walls and got great progress in parameter analysis and design method. For example, Nie [5] studied high strength concrete filled double steel plate composite wall with experiments and found that SC wall shows good behavior of energy consuming and deformation capacity, and can be used in high-rise building to resist earthquake. However, most of the research focus on the SC walls used in civil buildings with high shear span to depth ratio that leads to the flexural failure, while shear walls with small shear span to depth ratio mainly failed in shear mode. Some experiments and numerical simulations have been conducted to explore seismic behavior under in-plane and out-of-plane forces or moments. Xiong [6] conducted experiments of double steel plate concrete composite shear wall with studs and stiffeners under in-plane cyclic loading, and found that the SC walls have good deformation performance and strong shear resistance. Li [7-8] carried out experiments and finite element simulation of SC walls under out-of-plane force and the research shows that the thickness of steel plates, axial compression ratio and setup of stiffener has significant influence on the ductility of the SC shear walls.

In this study, simplified models of SC shear walls were established using finite element method (FEM) in ABAQUS and the simulation results were verified with the experimental results [9] focusing on the influence of shear span ratio, steel ratio and stud spacing in SC walls. Furthermore, the influence of steel ratio, axial compression ratio and shear span to depth ratio on the bearing and deformation
capacity of SC walls with small shear span ratio is studied. Based on the simulated results, the bearing and deformation characteristics of nuclear power structure with small shear span to depth ratio have been summarized.

2. Establishment of FEM models

2.1. Design of models

Finite element models were established and simulated in software ABAQUS based on specimens SCW1-1a and SCW1-1b with the same parameters from Cheng’s study [9]. Vertical load was applied at first and the model was controlled by in-plane horizontal displacement at the loading beam. A typical model was shown in Figure 1. Simplified models entitled “Composite Layup Shell” were used which assigned material properties layer by layer as a shell that leads to solving finite element equations easily and quickly. Although the local buckling of steel plates and the slippage between steel plates and concrete core were neglected, the reduction of stiffness and additional ductile damage model in ABAQUS were conducted to consider the local buckling and slippage. And this equivalent method is useful in evaluation of SC walls and simulation of full-scale structures.

For the purpose of exploring the influence of the thickness of steel plates, the axial compression ratio and shear span to depth ratio on the bearing capacity and ductility of SC walls, seven models with different parameters were established initially and four models were added to explore the quantitative relation between shear span to depth ratio and bearing capacity of SC walls. The properties of these models are illustrated in Table 1 in which $t_o$ is the thickness of steel plate, $\rho$ is the steel ratio, $\lambda$ is the shear span to depth ratio, and $n_d$ is the design axial compression ratio defined as formula (1):

$$n_d = \frac{1.25N}{f_c A_c/1.4+f_s A_s/1.1}$$

### Table 1. Properties of models

| Models   | Section (mm x mm) | Height (mm) | $t_o$ (mm) | $\rho$  | $\lambda$ | $n_d$ |
|----------|-------------------|-------------|------------|---------|-----------|-------|
| SCW1     | 1000x150          | 1000        | 3          | 5.20%   | 1.0       | 0.4   |
| SCW2     | 1000x150          | 1000        | 4          | 6.93%   | 1.0       | 0.4   |
| SCW3     | 1000x150          | 1000        | 5          | 8.67%   | 1.0       | 0.4   |
| SCW4     | 1000x150          | 1000        | 3          | 5.20%   | 1.0       | 0.2   |
| SCW5     | 1000x150          | 1000        | 3          | 5.20%   | 1.0       | 0.6   |
| SCW6     | 1000x150          | 400         | 3          | 5.20%   | 1.0       | 0.4   |
| SCW7     | 1000x150          | 700         | 3          | 5.20%   | 1.0       | 0.4   |
| SCW8     | 1000x150          | 500         | 3          | 5.20%   | 1.0       | 0.4   |
| SCW9     | 1000x150          | 600         | 3          | 5.20%   | 1.0       | 0.4   |
| SCW10    | 1000x150          | 800         | 3          | 5.20%   | 1.0       | 0.4   |
| SCW11    | 1000x150          | 900         | 3          | 5.20%   | 1.0       | 0.4   |

2.2. Materials

The steel support at the top and bottom of the model was assigned as elastic material with Young’s modulus and Poisson’s ratio 206000 MPa and 0.3, respectively. The yielding strength and ultimate strength of steel plates measured in Cheng’s study is 330 MPa and 477MPa. The constitutive model of steel plates was assigned as plasticity and ductile damage was also considered.

As for constitutive of concrete, the Young’s modulus and Poisson’s ratio are 33000 MPa and 0.2, respectively. The concrete damage plasticity (CDP) model was used to simulate the concrete in the two steel plates that was determined based on the Chinese Code GB50010-2010 (modified in 2015) and the modified model by Ren’s method [10] to adjust the input of ABAQUS. The Mander’s constitutive model for confined concrete was used to simulate the side part and side column [11] to consider the strong confinement of the core concrete.
2.3. Verification of models

Two sets of SC shear walls SCW1 (SCW1-1a and SCW1-1b have the same parameter in Cheng’s study for repeated experiments) and SCW2 (SCW1-4 in Cheng’s study) were used to verify the validity of the established models. The force-displacement curves of SCW1 and SCW2 were compared with the test skeleton curves of specimens SCW1-1a, SCW1-1b and SCW1-4, as shown in Figure 2.

From Fig 2, it is found that the curves’ shapes of the simulated and experimental results were similar, but the reaction forces of models at rising stage were a little larger than test results that probably resulted from the large deformation of steel plates and the reduction of concrete strength due to strong local buckling of steel plates that lead to the reduction of confinement. The peak forces and displacements of the simulated and the test results were closing, and so were the displacements at failure stage. The simulated peak forces were a little higher than those of test results.

2.4. Results of simulation

Based on the simulated results, equivalent energy method was used to calculate equivalent reaction force when steel yielding occurs. Ultimate displacement is the displacement when reaction force decreased to 0.85 of peak force. Ductility coefficient is defined as formula (2):

$$\mu = \frac{\Delta_u}{\Delta_y}$$  \hspace{1cm} (2)

where $\Delta_u$ – ultimate displacement before failure, and $\Delta_y$ – displacement when yielding occurs.

The calculated results of these characteristics are listed in Table 2.
Table 2. Results of models

| Models | Reaction Force(kN) | Displacement(mm) | Drift Angle | Ductility Coefficient |
|--------|-------------------|------------------|-------------|----------------------|
|        | Yield | Peak | Yield | Ultimate | Yield | Ultimate |                |
| SCW1   | 1494  | 1858 | 2.78  | 9.84     | 1/360  | 1/102    | 3.54         |
| SCW2   | 1803  | 2250 | 3.32  | 9.84     | 1/301  | 1/102    | 2.96         |
| SCW3   | 2109  | 2627 | 3.68  | 9.84     | 1/272  | 1/102    | 2.67         |
| SCW4   | 1492  | 1853 | 3.01  | 9.84     | 1/332  | 1/102    | 3.27         |
| SCW5   | 1477  | 1825 | 2.61  | 9.84     | 1/383  | 1/102    | 3.77         |
| SCW6   | 1740  | 2211 | 0.8   | 2.21     | 1/1250 | 1/452    | 2.76         |
| SCW7   | 1600  | 1991 | 1.69  | 4.54     | 1/592  | 1/220    | 2.69         |
| SCW8   | 1698  | 2146 | 1.12  | 2.79     | 1/893  | 1/358    | 2.49         |
| SCW9   | 1667  | 2054 | 1.38  | 3.79     | 1/725  | 1/264    | 2.75         |
| SCW10  | 1546  | 1948 | 2.04  | 5.33     | 1/490  | 1/188    | 2.61         |
| SCW11  | 1538  | 1903 | 2.41  | 6.61     | 1/415  | 1/151    | 2.74         |

3. Parameter analysis

3.1. Steel ratio
Steel ratio is highly related to the thickness of steel plates. The thickness of steel plates of models SCW1, SCW2 and SCW3 is respectively 3mm, 4mm and 5mm, i.e., 5.20%, 6.93% and 8.67%. The force-displacement curves of the models with different steel ratios were shown in Figure 3. A distinct enhancement was observed as the steel ratio increased which is because the bearing capacity of the steel increased. Moreover, the increase of thickness of steel plates also contribute to the resistance of local buckling.

3.2. Axial compression ratio
The axial compression ratio of models SCW4, SCW1 and SCW5 is respectively 0.2, 0.4 and 0.6. The force-displacement curves of models with different axial compression ratios were shown in Fig 4. There was almost no difference for models with different axial compression ratios within the range between 0.2 and 0.6. However, the ductility reduced as axial compression ratio increased.

3.3. Shear span to depth ratio
SC shear walls with shear span to depth ratio less than 1.0 are named as squat walls. Because all models have same sections with the dimensions of 1000×150mm, shear span to depth ratio is in a positive correlations with the wall height. The Shear span to depth ratio of the models SCW6, SCW7 and SCW1 is respectively 0.4, 0.7 and 1.0, i.e., 400mm, 700mm and 1000mm in height. The force-displacement curves of these models with different shear span to depth ratios were shown in Fig 5.

![Figure 3. Comparison of models with different steel ratio](image-url)
The ductility of the shear walls reduced as the shear span to depth ratio increased. The peak force was decreased as shear span to depth ratio became larger and the relationships can be reflected by linear. Four models with shear span to depth ratio 0.5, 0.6, 0.8 and 0.9 were added to obtain statistical analysis. The Pearson correlation coefficient between shear span to depth ratio and peak force is -0.990, which indicated the good correlation. Dispersed points and linear fitting were shown in Fig 6 and the estimated
standard error of linear fitting is 20.0, which means strong linear correlation between the peak force and the shear span to depth ratio.

4. Conclusion
According to the simulation results of the eleven SC shear walls, the main conclusions are as followings.

1. Composite layup shell is valid to simulate the double steel plate composite shear walls and SC shear walls have excellent mechanical performance.
2. Increasing steel ratio can enhance the capacity and ductility of the SC walls due to the fact that thicker steel plate provides stronger confinement to concrete and less local buckling of steel plates.
3. SC shear walls with lower axial compression ratio within the range 0.2 to 0.6 have better ductility.
4. The bearing capacity of SC shear wall shows linear decrease as shear span to depth ratio increases, while ductility decreases.

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