Modeling and Analysis of Composite Steel Plate Shear Wall with Assembled Multi-concrete Slab

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Keywords: Multi-concrete slab, Vertical assembling mode, Composite steel plate shear wall, Finite element method, ABAQUS.

Abstract. This paper presents numerical investigation of composite steel plate shear wall with vertical assembling mode (V-CSPSW) affecting cyclic loading. Three-dimensional finite element models are developed using ABAQUS emphasizing constitutive material modeling and element type to represent the real behavior of V-CSPSW. Validation of the FE model against the experimental results has shown a good agreement. The numerical studies were focused on the effects of gap width, bolt spacing-to-steel thickness ratio and concrete slab thickness on the V-CSPSW’s behavior. Results indicate that the gap width should less than 48mm and 72mm if the bolt spacing-to-steel thickness ratio is 100 and 125, respectively; meanwhile, the bolt spacing-to-steel thickness ratio of the V-CSPSW should less than 125 if the concrete slab possesses enough restraint stiffness.

Introduction

Composite steel plate shear wall (CSPSW) has high lateral stiffness, good energy dissipation capacity and ductility, which can provide an effective lateral force resisting system for high-rise building [1-4].

CSPSW consists of an infill steel plate and a reinforced concrete slab on both sides of the infill steel plate. The infill steel plate is prevented from buckling by the precast concrete slab effectively, ensuring that the infill steel plate resists lateral load in plane. Astaneh-Asl and Zhao put forward the steel plate-concrete composite shear wall, it divided into “traditional” and “innovative” models according to the connection type of precast concrete slab and the surrounding frame, the test of 3-story specimen and finite element analysis were conducted, it showed that the CSPSW has excellent ductility and energy dissipation capacity, but the damage of traditional model is more severe than that of innovative model [5,6]. Guo et al. proposed CSPSW connected with frame beams only, the results show that it can prevent the harmful effects on frame columns; moreover, it is convenient for the setting of openings of doors and windows [7-9].

Traditional CSPSW is assembled with single concrete slab, which has larger dimensions and is difficult for lifting and transporting. The single concrete slab was replaced by multi-precast concrete slab, CSPSW with assembled multi-concrete slab was proposed by authors. Three 1/3 scaled CSPSW specimens were made: composite steel plate shear wall with vertical assembling mode (V-CSPSW), composite steel plate shear wall with horizontal assembling mode (H-CSPSW) and traditional CSPSW. The cyclic loading test on specimens was performed. Among the horizontal and vertical assembling modes, the energy dissipation capacity, bearing capacity and stiffness of V-CSPSW are more superior. In this study, a number of V-CSPSW models were analyzed by utilizing finite element methods. The effects of gap width, bolt spacing-to-steel thickness ratio and concrete slab thickness upon the V-CSPSW’s behavior were investigated.
Finite Element Method

Models
In this paper, a number of one-story one-bay V-CSPSW models are taken into account. The models have different gap widths (gap=24, 48, 72, and 96 mm), bolt spacing-to-steel thickness ratio (λ=100, 125, 250, and 500 mm) and concrete slab thickness (d_s=50, 75, 100, and 125 mm); furthermore, there is a 60 mm gap between steel boundary elements, beams and columns, and the reinforced concrete slab.

It is considered that only infill steel plate resist lateral load corresponding to the full shear yield of infill steel plate; hence, the boundary elements are designed to ensure this principle. Plastic hinges are expected to merely locate at beams or the bottom of columns. The boundary elements are designed in accordance with technical specification for steel plate shear walls [10]. The designed sections for beams and columns are HM194×150×6×9 and HW200×200×8×12 respectively, as shown in Fig. 1. The details of calculated models are given in Table 1, and a typical model of V-CSPSW is illustrated in Fig. 1, with the infill steel plate L/h=1, h=1200 mm, and L=1200 mm.

<table>
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<th>Models</th>
<th>gap [mm]</th>
<th>d_s [mm]</th>
<th>λ=dp/t_s</th>
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<th>Models</th>
<th>gap [mm]</th>
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Remark: The model of G24-L100-C50 means gap width is 24 mm, bolt spacing-to-steel thickness ratio is 100 and the concrete slab thickness is 50 mm.

Numerical Modeling

The large-scale finite element software, ABAQUS/Standard, is utilized for cyclic analyses of seismic behavior of V-CSPSW. Shell elements (S4R) are selected for the infill steel plate, beams and columns.
Solid elements (C3D8R) are chosen for the concrete slabs. 2-node three-dimensional elements (T3D2) for reinforcements are utilized. Fig. 2 shows finite element model of V-CSPSW.

The bolts connect the reinforced concrete slabs to the infill steel plate. The stress and deformation of the bolt is not the main object of this paper. The BEAM type connection element is used to simulate the bolt. In order to ensure the accuracy and convergence of the analysis, the steel mesh size is taken as the 1/20 of the long side of the steel plate, that is to say, the mesh size is 60mm. According to the actual installation process, there is a certain gap between the steel plate and the concrete slab on both sides, the gap will reduce the stiffness of the shear wall. Thus the gap is set to 3mm in the finite element model. In addition, the hard contact used in normal direction and Coulomb friction used in tangential direction of the contact between the infill steel plate and the concrete slabs on both sides, and the friction coefficient is 0.1.

In V-CSPSW models, by introducing the shape of the first 3 order buckling modes to simulate the initial imperfections of the steel plate, the initial imperfection magnitude is taken as 1/1000 of the long side of the steel plate.

**Material Constitutive Models.** Q235 ($f_y=235\text{MPa}$) and Q345 ($f_y=345\text{MPa}$) are selected for infill steel plate and boundary members respectively. The bilinear kinematic hardening model is chosen for the constitutive model of the steel, the Yong's modulus, yield strength and the Poisson's ratio are obtained by test of mechanical properties. Table 1 shows mechanical properties of steel.

The concrete damaged plasticity model in ABAQUS is utilized for the concrete material. The concrete damaged plasticity approach considers both tensile and compressive failures of concrete material, which is a three-dimensional continuum plasticity-based model. The compressive strength is 40MPa and the complete comparison stress–strain curve is derived by using Mander unconfined concrete stress–strain approach. Fig. 3 shows compression and tensile stress–strain curves.
Table 2. Mechanical properties of steel.

<table>
<thead>
<tr>
<th>Location</th>
<th>Yield strength $f_y$(MPa)</th>
<th>Ultimate strength $f_u$(MPa)</th>
<th>Young’s modulus $E_s$(Mpa)</th>
<th>Elongation $\Delta$(%)</th>
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<td>Infill steel plate</td>
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<td>Beam</td>
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<td>483</td>
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<td>Rebar</td>
<td>632</td>
<td>637</td>
<td>$1.26\times10^5$</td>
<td>25.5</td>
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</table>

Loading Procedure and Boundary Conditions. In order to conduct the cyclic analyses, by setting reference point that is coupled with loading position of beam, and the horizontal displacement is applied on reference point. The loading mode is consistent with test loading scheme. In finite element models, the out-of-plane degree of freedoms of top beam are fixed; moreover, all six degrees of freedom of bottom nodes for both columns and beam are restrained to stimulate the fixed condition.

Validation

The obtained finite element analyses results, compared with experimental results, attest that the finite element modeling can reasonably predict the behavior of V-CSPSW. Fig. 4 shows comparisons of experimental results and the obtained numerical results. It illustrates that ultimate bearing capacity for experimental specimen and finite element model are 881.0 kN and 986.9 kN, respectively, showing 12% differences in maximum values. Fig. 5 shows that the stress distribution of the infill steel plate is consistent with the experimental failure characteristics. Even though care was taken in modeling and simulating the structures closely, there were slight differences between the experimental and the numerical models. This is mainly because each part of the component is assumed to be an ideal connection and the assumed bilinear behavior of the steel materials differs from their real behavior.

Discussion of Results

Influence of Gap Width

“Lateral load-displacement” curves are used to evaluate the effect of the gap width upon the behavior of V-CSPSW. Different gap widths (24, 48, 72, and 96mm) are attached to a variety of bolt spacing-to-steel thickness ratio (100, 125, 250, and 500). As show in Fig. 6, it can be seen that with the increase of gap width, the shear strength of V-CSPSW is reduced in a certain extent, but the bolt spacing-to-steel thickness ratio has a direct effect on it. When the bolt spacing-to-steel thickness ratio is 100 and 125, respectively, the gap width is more than 48mm and 72mm, the shear capacity of composite steel plate shear wall decreased significantly. However, if the bolt spacing-to-steel thickness ratio is greater than 250, the gap width has little effect on shear capacity of composite shear wall. It mainly due to the larger bolt spacing-to-steel thickness ratio, that is, the bolt distribution is sparse, with insufficient restraint stiffness of concrete slabs, thus, the infill steel plate gradually
showed the unconstrained stress state. Then, the effect of gap width is insignificant on behavior of CSPSW.

V-CSPSW with different gap widths has different energy dissipation. Fig. 7 depicts the energy dissipation with a variety of bolt spacing-to-steel thickness ratios. It can be rationally conclude that the energy dissipation decreases with the increase of gap width, and it is related to the bolt spacing-to-steel thickness ratio.

![Figure 6. Capacity-displacement curve.](image)

**Influence of Bolt Spacing-to-steel Thickness Ratio and Concrete Slab Thickness**

As shown in Fig. 8, with the bolt spacing-to-steel thickness increases, the hysteretic curves has pinch phenomenon. In order to ensure the composite steel plate shear wall has good energy dissipation capacity, the bolt spacing-to-steel thickness ratio of the V-CSPSW should less than 125 if the concrete slab possesses enough restraint stiffness. Increasing the concrete slab thickness develops energy dissipation. It mainly due to the restraint stiffness is higher with concrete slab thickness increase, which can prevent infill steel plate from buckling effectively, ensuring that the infill steel plate resists lateral load in plane. However, it related to the bolt spacing-to-steel thickness ratio. If the bolt distribution is dense and concrete slab thickness can ensure sufficient restraint stiffness, then the concrete slab thickness has little effect on behavior of composite steel plate shear wall.

Fig. 9 depicts out-of-plane deformation of infill steel plate with different bolt spacing-to-steel thickness ratios. It can be seen that the out-of-plane deformation increase with the bolt spacing-to-steel thickness ratio increases, the infill steel plate gradually forms an obvious tension field, and its deformation form is close to the deformation mode of the ordinary steel plate shear wall.
Figure 8. The hysteric curves.

Figure 9. Out of plane deformation of infill steel plate.
Conclusions

In this study, a number of numerical models for calculating the behavior of V-CSPSW are considered. Based on the validated model, a parametric study was performed on it to study the effects of gap width, bolt spacing-to-steel thickness ratio and concrete slab thickness. The main results can be summarized as follows:

1- The skeleton curves and the failure characteristics of the experimental and numerical V-CSPSW are compared. It is found that the simulation outcomes have showed good agreement with the experimental results.

2- In order to ensure the composite steel plate shear wall has good lateral resisting capacity, the gap width should less than 48mm and 72mm if the bolt spacing-to-steel thickness ratio is 100 and 125, respectively.

3- The bolt spacing-to-steel thickness ratio of the V-CSPSW should less than 125 if the concrete slab possesses enough restraint stiffness.

Acknowledgement

This project is supported by the National Science Foundation of China (51408140, 51378135), Guangzhou Yangcheng scholars program (1201581632) and Guangdong outstanding young teachers project (Yq201402), which are gratefully acknowledged.

References


