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Shear force demand on headed stud for the design of composite steel plate shear wall

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ABSTRACT

Composite steel plate shear wall (C-SPW) consisting of steel plate with reinforced concrete encasement on one or both sides of the steel plate using headed studs is an effective lateral load resisting system. Previous researches focus mainly on its seismic behavior, while few researchers pay attention to the shear force demand on headed stud, which is an important issue in the design of C-SPW. In this paper, an investigation on the shear force demand on headed stud for the design of C-SPW is carried out by finite element analysis. A novel finite element model incorporating an effective simulation of boundary frame as well as reasonable interaction behaviors of elements is established using ABAQUS and validated in comparison with available tests. The responses of structural elements in C-SPW under monotonic lateral load are investigated. The effects of headed stud diameter, infill steel plate thickness, concrete panel thickness, number of headed studs as well as aspect ratio of shear wall on the maximum stud shear force are analyzed. Based on the analysis results, an available formula for the demand on stud shear force in the design of C-SPW is proposed.

1. Introduction

Shear wall systems are widely adopted as lateral load resisting systems in high-rise buildings, which are commonly categorized into reinforced concrete (RC) shear wall, steel plate shear wall (SPSW) and composite steel plate shear wall (C-SPW). C-SPW consisting of steel plate with reinforced concrete encasement on one or both sides of the steel plate using mechanical connections such as headed studs is an effective lateral load resisting system with significant ductility, stiffness and energy dissipation capacity. Compared to an RC shear wall, a C-SPW with the same shear capacity and shear stiffness has less weight. In addition, RC shear wall can develop tension cracks and localized crushing during large displacement. Unstiffened SPSWs carry lateral loads by diagonal tension field action after their buckling, which leads to a decrease in shear capacity, shear stiffness and energy dissipation of the system. In C-SPW, concrete encasement prevents the infill steel plate buckling before yielding. As a result, the load-resisting mechanism changes from diagonal tension field action to in-plane shear yielding. Thus, the shear capacity and shear stiffness as well as energy dissipation capacity of shear walls are improved. The concrete panel can also provide sound and temperature insulation as well as fire proofing to the infill steel plate.

To date, a number of researches on C-SPW have been reported. These researches focus mainly on seismic behavior of C-SPW, while few researchers pay attention to its design method. The design guidelines for C-SPW have not been completed yet.

The study on C-SPW starts with Zhao and Astaneh-Asl [1,2]. Cyclic static tests were conducted on two types of specimens named traditional and innovative C-SPW. The test specimens were one-bay three-storey consisting of steel plate shear walls welded inside a steel boundary frame and pre-cast concrete panels bolted to the one side of steel plate. The specimens had identical properties except that there are 32 mm gaps between concrete panel edges and steel boundary frame in innovative one. Both specimens demonstrated highly ductile and stable inelastic behavior.

Provisions combining with the minimum thickness of concrete panel, minimum reinforcement ratio as well as minimum spacing between rebars in C-SPW are specified by AISC 341-10 [3].

Dey and Bhowmick theoretically developed a formula for calculating the minimum concrete panel thickness and the maximum stud spacing in C-SPW [4]. The analysis was based on the condition that the buckling strength of subpanels surrounded by stiffeners and stiffened plate must be greater than their yielding shear strength after transforming the concrete panel to vertical and horizontal concrete stiffeners along the shear stud lines. The buckling

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of rectangular subpanel with all edges clamped and the whole stiffened plate subjected to shear force were checked using elastic buckling theory. It should be noticed that this formula for the minimum thickness of concrete panel is conservative.

Both Smith et al. [5] and Arabzade et al. [6] proposed the local buckling coefficient for a unilaterally constrained rectangular plate under shear force using Rayleigh-Ritz method. The latter one was proved to be effective in comparison with the test results of C-SPWs with cast-in-place concrete panel on one side of steel plate [7].

There have been a few of experimental and numerical researches on the effects of design parameters on the seismic behavior of C-SPWs in recent years. Rahai and Hatami conducted numerical and experimental investigations on the effect of stud spacing on the overall behavior of C-SPWs [8]. The results revealed that the energy dissipation increased and the out-of-plane displacement in steel plate decreased with the increase of stud spacing. Guo et al. conducted an experimental research on the cyclic behavior of C-SPW in composite frame [9]. They pointed out that these C-SPWs have good ductility and excellent energy dissipation. Shafaei et al. performed numerical analyses on the effect of concrete panel thickness on the behavior of C-SPW [10]. Rahnavard et al. carried out a numerical study on the hysteretic behavior of C-SPW [11]. The effects of concrete panel thickness and shear connector spacing on the out-of-plane displacement, the maximum interstorey drift as well as energy dissipation of five types of C-SPWs were investigated. The comparison between light-weight and normal-weight concrete panel in C-SPWs was undertaken by Rassouli et al. using experimental and numerical analyses [12]. The obtained results demonstrated that light-weight concrete panels can be used as a stiffener instead of normal-weight ones in C-SPWs, which reduces a considerable seismic mass and improves the behavior of steel structures.

An innovative type of C-SPW, named buckling-restrained steel plate shear wall (BR-SPW), was proposed by Guo and Dong [13,14]. The diameter of preformed hole in the pre-cast concrete panel is larger than the bolt diameter. As a result, there is no tangential interaction between infill steel plate and concrete panel. Experimental research on cyclic performance of BR-SPW, C-SPW and SPSW was conducted. The test results revealed that the damage to concrete panel in BR-SPW is little during large cycles, which leads to an improvement in energy dissipation capacity of infill steel plate. Jin and Ou et al. carried out theoretical and numerical analyses on the stability of a novel BR-SPW with inclined slots [15] and the relevant design recommendations were provided based on the analysis results.

The nominal shear strength of headed stud in composite structure is specified in AISC 360-05 [16], Eurocode 4 [17], ACI 318-11 [18] as well as PCI 6th Edition [19] and was comprehensively investigated by Pallarés et al. [20] and Xue et al. [21], but no researcher pays attention to the shear force demand on headed stud in the design of C-SPW.

In this paper, the demand on stud shear force in traditional C-SPW, which is characterized by cast-in-place reinforced concrete encasements on both sides of infill steel plate and no gap between concrete encasements and boundary frame, is studied using finite element analysis. A novel finite element model incorporating an effective simulation of boundary frame as well as reasonable interaction behaviors of elements is established using ABAQUS and validated in comparison with available tests. The responses of structural elements in 29 specimens of C-SPW under monotonic lateral load are investigated; the development and distribution of shear force in stud group are illustrated; the effects of headed stud diameter, steel plate thickness, concrete panel thickness, number of headed studs as well as aspect ratio of shear wall on the maximum stud shear force demand are analyzed; based on the analysis results, an available fitting formula for the demand on stud shear force in the design of C-SPW is proposed.

2. Finite element model of C-SPW

A novel finite element model (FEM) of C-SPW that can simulate the boundary frame and takes into account the interaction of infill steel plate, concrete panels, boundary frame and headed studs is developed using ABAQUS/Standard [22] and is validated by comparing with the results of available tests.

2.1. Material properties

In ABAQUS, the constitutive behavior of concrete is modeled using a plastic damage (CDP) model [23,24], which is found to be suitable for concrete subjected to monotonic and cyclic loads, as shown in Fig. 1. Damage parameters (d_t and d_c) and stiffness recovery factors (w_t and w_c) depict the elastic stiffness degradation during unloading and stiffness recovery during the load reversal, respectively.

The relationships of tensile stress-strain (σ_t-ε_t) and compressive stress-strain (σ_c-ε_c) utilized in CDP model commonly refer to the data from uniaxial compressive and uniaxial tensile test on concrete [25–27]. These relationships (represented by solid line in Fig. 1) adopted in this work are depicted using Eqs. (1) and (2).

$$\begin{cases} \varepsilon_t = x_t \cdot \varepsilon_{t,r} \\ \sigma_t = y_t \cdot f_{tk} \end{cases}; \; y_t = \begin{cases} \frac{E_c \varepsilon_{t,r}}{f_{tk}} x_t & x_t \leqslant 1 \\ \frac{x_t}{\alpha_t (x_t - 1)^{1.7} + x_t} & x_t > 1 \end{cases} \tag{1}$$

$$\begin{cases} \varepsilon_c = x_c \cdot \varepsilon_{c,r} \\ \sigma_c = y_c \cdot f_{ck} \end{cases}; \; y_c = \begin{cases} \frac{x_c n}{n - 1 + x_c^n} & x_c \leqslant 1 \\ \frac{x_c}{\alpha_c (x_c - 1)^2 + x_c} & x_c > 1 \end{cases} \tag{2}$$

where f_{tk} and f_{ck} are nominal tensile strength and nominal compressive strength of concrete in MPa, respectively; the strain corresponding to f_{tk} and f_{ck} are $\varepsilon_{t.r}$ and $\varepsilon_{c,r}$ which are calculated as $\varepsilon_{t,r} = f_{tk}^{0.54} \times 65 \times 10^{-6}$ and $\varepsilon_{c,r} = (700 + 172\ f_{tk}^{0.5}) \times 10^{-6}$; E_c is the Young's modulus of concrete; dimensionless factors α_t, α_c and n are computed as $\alpha_t = 0.312\ f_{tk}^2$, $\alpha_c = 0.157\ f_{ck}^{0.8} - 0.905$ and $n = E_c \varepsilon_{c,r} / (E_c \varepsilon_{c,r} - f_{ck})$, respectively.

In order to simulate the unloading behavior in concrete, damage parameter in compression (d_c) and in tension (d_t) are introduced in CDP model. d_c and d_t are respectively calculated using Eqs. (3) and (4), where β varies from 0.5 to 0.95.

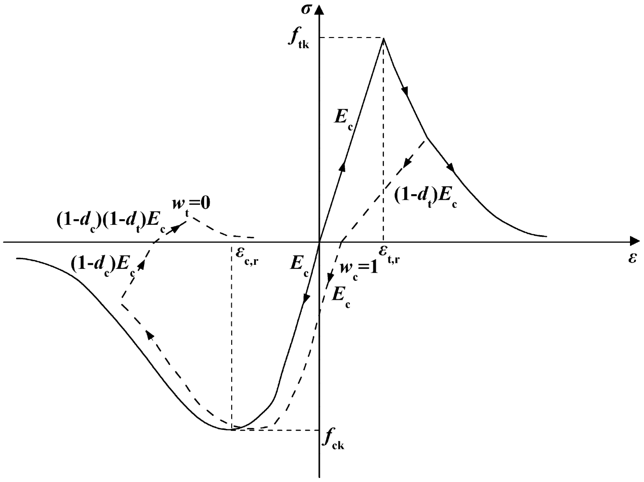

Fig. 1. Constitutive relationship of concrete.