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Numerical study of concrete-filled steel plate composite coupling beams

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ABSTRACT

Concrete-filled steel plate (CFSP) composite coupled shear wall systems consisting of two or more CFSP composite wall piers connected by CFSP composite coupling beams are efficient seismic resisting systems for high-rise buildings. A nonlinear finite element model that can simulate the load–deformation behavior and local response of CFSP composite coupling beams was developed to investigate their deformation and force mechanisms. Although the beam end rotation contributes largely to the lateral displacement in the initial loading stage because of local deformations at the connection regions, the flexural and shear deformations of the coupling beam are the main contributors when the coupling beam deforms into plasticity. The ratio of flexural to shear contributions to lateral displacement is affected significantly by the beam span-to-height ratio and ratio of steel flange thickness to web thickness. The effective sectional stiffness of CFSP composite coupling beams can be taken as the sum of the full stiffness of the steel plates and a reduced stiffness provided by the concrete infill. Because of the compression resistance provided by the diagonal compression strut formed in the concrete infill, the steel web plates tend to sustain tension forces, and shear forces are sustained mainly by the web plates in the compression region. For the common coupling beams, the steel plates resist 36–76% of the shear force, and 57–82% of the beam end moment, and the remainder of the internal forces is resisted by the concrete infill.

1. Introduction

Coupled shear wall systems that consist of two or more shear walls connected by coupling beams are efficient lateral force resisting systems, and have been used extensively in seismic areas. Concrete-filled steel plate (CFSP) composite coupled shear wall systems are new structural systems that have been developed by the authors [1]. Their intended use is in super high-rise buildings in which internal forces are too large to be withstood by conventional reinforced concrete (RC) structures. As shown in Fig. 1, the proposed coupled shear wall system consists of two or more CFSP composite wall piers connected by CFSP composite coupling beams. Given that the two structural elements have similar configurations (both consist of surface steel plates and concrete infill), it is easy to design them with matched stiffness, load-carrying and deformation capacities.

In the past three decades, great efforts have been made to develop new forms of coupling beams to improve the seismic performance of coupled shear walls. In the U.S., steel coupling beams were recommended to couple reinforced concrete shear walls. Pushover analysis [2,3] and nonlinear dynamic analysis [4] were conducted on this hybrid coupled shear wall system, and design procedures [5] were also proposed.

Steel plate-reinforced concrete composite coupling beam is another well-developed coupling beam. Extensive studies including experimental study [6,7], finite element analysis [8] and design procedure development [9] were conducted on this type of coupling beam. It was found that the embedded steel plates could improve the strength and stiffness of coupling beams, and alleviate the pinching problem of conventional RC coupling beams. Shear studs were required to provide sufficient load transfer between the steel plate and concrete in order to achieve good inelastic performance at large shear deformations.

The composite coupling beam proposed by Gong and Shahrooz [10] was similar to the steel plate-reinforced composite coupling beam, while the embedded steel plate was replaced by an I-shaped steel beam. Component and subassembly testing [11] were both

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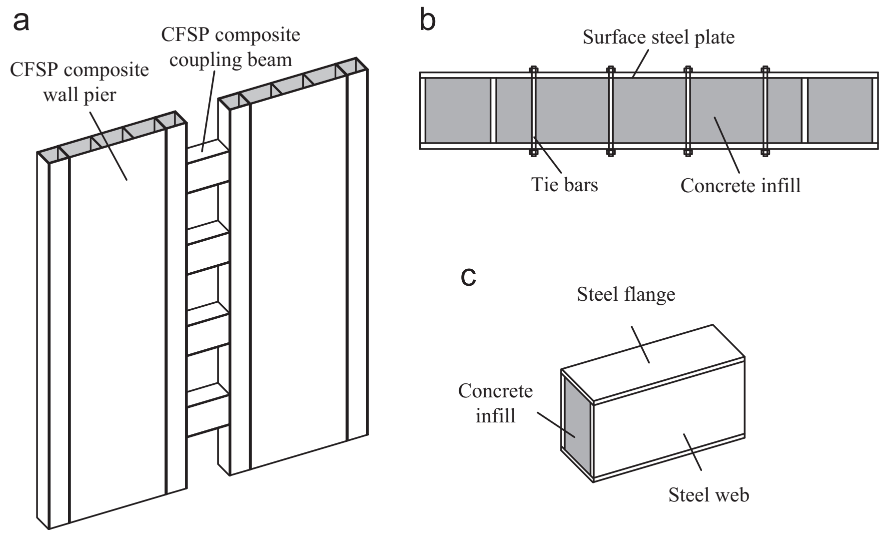

Fig. 1. Details of the CFSP composite coupled shear wall system: (a) Overview of the CFSP composite coupled shear wall system; (b) Cross section of the CFSP composite wall pier; (c) CFSP composite coupling beam.

carried out to study the seismic behavior of these composite coupling beams, their connections to reinforced concrete walls, and the overall behavior of composite coupled wall system. Based on the experimental studies, guidelines for proper design and detailing of the composite coupling beams and beam-wall connections were proposed [12].

Steel plates were also used as a retrofit method to strengthen reinforced concrete coupling beams. In the tests of Su et al. [13] and Cheng et al. [14], the reinforced concrete coupling beams were strengthened by bolted external steel plates on the side faces of the coupling beams. The experimental results showed that this retrofitting method could effectively increase the deformation and energy dissipation capacities of both the medium-span and deep reinforced concrete coupling beams.

Several studies have been conducted on the flexural behavior of square and rectangular concrete filled steel tubular (CFST) members. Lu and Kennedy [15], Uy [16], Han [17], and Han et al. [18] used simply supported beam tests to investigate the behavior of square and rectangular CFST members under pure bending. In the tests of Tomii and Sakino [19], Fujimoto et al. [20] and Varma [21], the CFST members were subjected to constant axial compression and increasing bending moment. The parameters varied in these tests mainly included the depth-to-width ratio of the section, the width-to-thickness ratio of the steel tube plates, the concrete compressive strength and the steel yield strength. The CFSP composite coupling beam is one kind of CFST members, but the behavior of CFSP composite coupling beams is usually dominated by the shear force or both the shear and flexural force because of their small shear span ratios. The behavior of CFST members with small shear span ratios was seldom investigated in the previous studies. This is another motivation of this study.

Experimental studies have been conducted on the CFSP composite shear walls [22] and coupling beams [1]. Tests on CFSP composite coupling beams included subjecting six coupling beam specimens with varying span-to-height ratio, steel plate thickness, and bending-to-shear capacity ratio to reversed cyclic loading [1]. The progression of limit states, hysteretic behavior, deformation capacity, and energy dissipation of the coupling beams were studied.

This paper reports on a subsequent study of CFSP composite coupling beams, in which we attempt to study the deformation and force mechanisms of CFSP composite coupling beams using finite element methods (FEM). We aimed to develop a detailed finite element model that can well simulate the global and local behavior of CFSP composite coupling beams, so that their deformation and force mechanisms can be studied comprehensively. The results of this study provide a basis for computing shear capacity and for developing a simplified beam element model for CFSP composite coupling beams.

2. Experimental outline

More detailed information regarding the experimental program on the concrete-filled steel plate composite coupling beams can be found in Ref. [1]. Six specimens were designed and constructed with coupling beams between two shear wall piers as shown in Fig. 2. The wall piers were attached rigidly to end plates that allowed the specimen to be bolted to the test setup. The coupling beam width and height were 150 mm and 300 mm, respectively. The shear wall thickness was 150 mm and consisted of concrete-filled steel sections with a 5 mm steel plate thickness for all specimens. Parameters that were varied between specimens included the coupling beam span and steel plate thickness used for the coupling beam. Key parameters for the specimens are shown in Table 1. The difference between specimens CFSCB-4 and CFSCB-6 was the location of the splice for steel web plates; CFSCB-1 to CFSCB-5 had web plate splices at the ends of the coupling beam and CFSCB-6 had a web plate that was continuous onto the wall pier.

A schematic diagram of the test configuration is shown in Fig. 3. Specimens were connected to the foundation girder and an L-shaped loading girder at an orientation that is rotated 90° from their actual orientation in a building to be attached into the test setup. The two end plates had 22 10.9s-grade M30 high-strength bolts on each side. The shear force was applied using a 1000 kN servo-hydraulic actuator acting along the centerline of the coupling beam span to direct the inflection point to the mid-span of the coupling beam. The actuator location in conjunction with the four-bar mechanism that restricted rotation of the L-shaped loading girder simulated typical boundary conditions that were expected in real buildings. The specimens were subjected to reversed cyclic loading with a gradual increase in lateral displacement.