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Seismic behavior of shear walls with boundary CFST columns and embedded multiple steel plates: Experimental investigation

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ABSTRACT

In this study, an innovative composite shear wall, comprised of boundary Concrete Filled Steel Tubular (CFST) columns, and Reinforced Concrete (RC) walls embedded with multiple steel plates has been developed. Seven specimens were investigated by cyclic loading tests. The parameters were the type of the boundary CFST columns, the number of multiple steel plates and the axial force ratio. There were two loading stages for the tests. During stage 1, the specimens were tested until a 2.0% drift ratio was attained. After stage 1, damaged specimens were retrofitted and tested in stage 2. The failure characteristics, hysteretic behavior, strength and deformation, strains, energy dissipation capacity and stiffness were studied. The results show that the hysteresis curves of the innovative shear walls were stable. The embedded multiple steel plates had a considerable effect on the seismic behavior of the innovative shear walls, and the strength increased with increasing number of steel plates. There was no considerable difference in the effect on seismic behavior for the different types of the boundary CFST columns. The developed shear walls, after retrofitting, were shown to satisfy seismic requirements. Finally, an evaluation method for the ultimate strength of the shear walls was developed with adequate accuracy.

1. Introduction

Reinforced concrete (RC) shear walls are commonly used in high-rise buildings as they are important components for resisting earthquakes [1,2]. However, in most cases, the axial force ratio of the shear walls is limited according to the seismic design codes of different countries [3–5]. In high-rise buildings, the axial force in the low stories is usually very large. As a result, the wall needs to be designed with dense reinforcing bars and thick sections. The consequences are that it will be more difficult to layout the reinforcing bars, and it also amplifies the earthquake action due to the increase in weight of the structure. Furthermore, increasing the wall thickness reduces the available area. Hence, in high-rise buildings, the design and construction of RC shear walls is very difficult. Sometimes, it is even impossible.

To overcome the RC shear walls' problems mentioned above, Steel Plates Embedded Reinforced Concrete (SPE-RC) shear walls have been developed in recent years [6], and the design provisions are specified in the Chinese code [7]. Fig. 1(a) shows the schematic view of a traditional SPE-RC shear wall. Usually, for an SPE-RC shear wall, the main components are the embedded single full-size steel plate, RC wall and boundary CFST columns [8–11]. However, traditional SPE-RC shear walls have the following disadvantages: (1) The embedded single steel plate is continuous and the size of the entire wall, as such, it is difficult to hoist, to place into its desired location, and to weld. (2) As the embedded single steel plate separates the concrete into two parts, when the shear wall is under a large axial force, the concrete wall may be split into two. In order to prevent the wall from splitting and to improve integration, shear studs or bolts are welded on both sides of the steel plate. However, the cost of welding the shear studs is high and the construction is difficult.

In this study, an innovative shear wall with boundary CFST columns and embedded multiple steel plates has been developed based on the traditional SPE-RC shear wall. Fig. 1(b) shows the schematic view of the innovative composite shear wall. As shown, instead of the single full-size steel plate in the traditional SPE-RC shear wall, multiple steel plates are embedded inside the walls. As compared to a single steel plate, the merits of the multiple steel plates are as follows: (1) Less steel required. (2) As the multiple steel plates are smaller and lighter than the single full-size steel plate, they are easier to hoist, to place into the desired locations and to weld, leading to an easier construction. (3) The integrity of the concrete wall is improved because concrete on the two sides is connected through the gaps between the multiple steel plates. (4) The construction work is simplified because there is no need for welding shear studs or bolts to the steel plate.

In the middle of the innovative shear wall, as shown in Fig. 1(b), an additional boundary CFST column is used to enhance ductility and to

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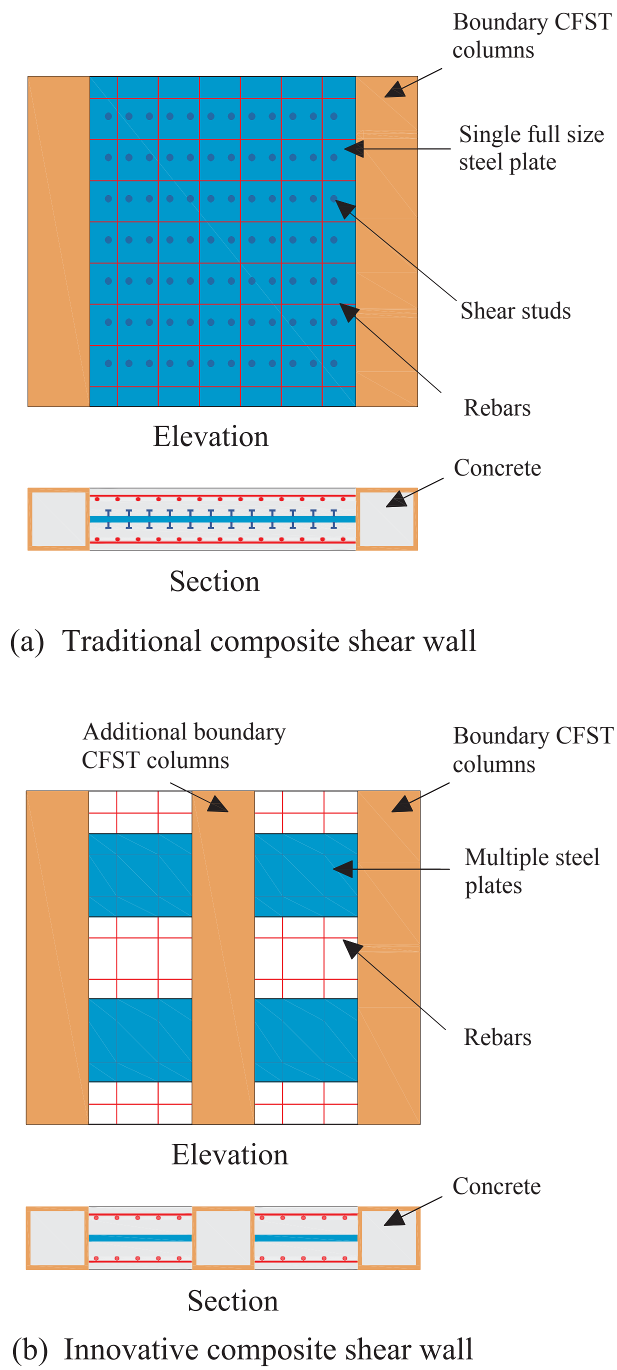

Fig. 1. Schematic view of the traditional and innovative SPE-RC shear wall.

carry part of the axial load. Since the RC wall was divided into two slender walls by the additional boundary CFST column, the displacement capacity of the shear wall can be increased. In Ref. [12], the I-shaped steel was used in the middle of the shear wall to form the Steel Reinforced Concrete (SRC) column. The test results showed that the middle SRC column experienced severe damages. Furthermore, the construction of the SRC column is difficult in engineering practice. In order to overcome these problems, this study used the CFST column rather than the SRC column, as shown in Fig. 1(b).

The present paper reports the cyclic tests of seven innovative shear walls. There were two loading stages for the tests. During stage 1, the specimens were tested until a 2.0% drift ratio was attained. After stage 1, damaged specimens were retrofitted and tested in stage 2. The failure characteristics, hysteretic behavior, strength and deformation, strains, energy dissipation capacity and stiffness were studied. An evaluation method for ultimate strength was developed.

2. Experimental program

2.1. Design of test specimens

A total of seven specimens were designed at approximately 1:5 scale. Table 1 and Fig. 2 show the details of the specimens. The parameters varied for the test were: (1) Number of embedded multiple steel plates m, where m = 0, 2, 3, 4; while specimen S5N1 had a single full-size steel plate to compare the traditional approach to the innovative shear walls with multiple steel plates proposed; (2) The boundary CFST columns type, i.e. square or circular CFST columns; (3) Whether retrofitting work was performed; (4) Axial force ratio n = 0.15 or 0.25. In accordance with the JGJ 3-2011 provisions [13], the axial force ratio n was calculated as follows:

$$n = N/(f_c' A_c + f_y A_s) \tag{1}$$

where N is the axial force, A_c is the concrete area; f_c' is the concrete cylinder compressive strength; f_y is the yield strength of steel; A_s is the total steel area.

Specimen S0N2R is used as an example to explain the specimens' ID in Table 1. (1) S refers to square CFST column, while C refers to circular CFST column; (2) 0 refers to the absence of steel plates, while 2 refers to two steel plates, 3 refers to three steel plates, 4 refers to four steel plates and 5 refers to a single full-size steel plate; (3) N refers to a normal axial force ratio = 0.15, while H refers to a higher axial force ratio = 0.25; (4) 2 refers to stage 2, while 1 refers to stage 1; (5) R refers to a retrofitted specimen.

The overall dimensions of the wall were 960 mm in height and 740 mm in width. The aspect ratio (i.e., height-to-width ratio) was approximately 1.5. The thickness of the RC wall was 140 mm. The loading beams and foundations consisted of rectangular steel boxes filled with concrete. The sizes of the square and circular steel tubes were 140 mm × 140 mm × 4 mm and 160 mm × 5 mm, respectively. The embedded multiple steel plates and CFST columns were connected by full penetration welding. Each steel plate was 160 mm × 160 mm × 4 mm. Fig. 2(c) shows the core steel structure of the specimens.

Reinforcing bars D4 (4 mm diameter) were used for horizontal and vertical reinforcement in the RC wall. The horizontally-distributed bars were welded to the steel tubes. To improve the integrity between the multiple steel plates and the concrete, D4 (4 mm diameter) tie bars were installed through the gaps between the steel plates.

In order to ensure proper anchorage, the vertically distributed reinforcing bars and boundary steel tubes were extended to the bottom of the foundation and the top of the loading beam. Furthermore, three D25 (25 mm diameter) reinforcing bars were inserted through the steel tubes inside the foundation and two inside the loading beam to enhance the anchoring of the walls. Bolts (6 mm in diameter, spaced 60 mm on center) were welded to the steel tubes along the interface between the steel tubes and the RC walls, to enhance the bonding and friction, as shown in Fig. 2(d).

2.2. Material properties

2.2.1. Concrete

The CFST columns, shear walls, foundation and loading beam were cast with the same concrete. The strength grade of the concrete used was C45 according to the Chinese code [14] (i.e. the nominal cubic compressive strength f_{cu}^{150} = 45.3 N/mm²). In the Chinese codes, cubic tests are performed on 150 mm × 150 mm × 150 mm cylinders. The concrete cylinder compressive strength f_c' can be calculated based on Eq. (2)[14]. According to this equation, the concrete cylinder