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Seismic performance of steel–concrete composite structural walls with internal bracings

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ABSTRACT

This paper presents experimental and analytical investigations of steel–concrete composite structural walls with internal bracings. In the experimental study, four full-scale wall specimens were tested under cyclic load reversals. The performance of the wall specimens in terms of load–deformation response and cracking patterns is described. However, due to the inherent complexity of shear walls and unique features of the embedded diagonal bracing, the experimental investigation was not sufficient to fully explain the influence of several parameters. Therefore, an analytical investigation based on the FE models using DIANA is presented. Validation of the FE models against the experimental results has shown a good agreement. Critical parameters influencing the shear wall's behavior such as shear span ratio, axial load, the size and thickness of shaped steel are varied, and their effects on the walls' seismic behavior are discussed.

1. Introduction

Owing to the combination of advantages of reinforced concrete and steel plates, steel–concrete composite structural walls have demonstrated superiorities in strength stiffness and ductility [5], which make them favorable worldwide, especially in the high seismic regions such as China and Japan. From the study of Synge [13], it is also noticeable that diagonal bracings can be introduced in shear walls as an effective approach to withstand shear force and improve the energy dissipation capacity. By adding inclined bracings in the steel–concrete composite structural walls, steel buckling, crushing and spalling of concrete and tensile cracks can be effectively reduced according to the experiment conducted by Astaneh and Zhao [1].

In spite of the wide application of steel–concrete composite structural walls, the complexity of the combination of steel and concrete makes it difficult to understand their behaviors. Scholars have done quite a number of experiments in this area. Emori [5] conducted compression and shear test 1/4 scale specimens on concrete filled steel box walls, concluding that the resisting effect of concrete on the local buckling of the steel plates as well as the confinement effect of steel plates on concrete gave the composite structure high strength and sufficient ductility. In an attempt to simulate the behavior of composite concrete–steel plate walls, Link [10] developed a series of FE analyses, finding that the strength degradation was effectively inhibited by introducing two layers of steel plates, making the walls more ductile. As an effort to study the energy dissipation behavior of shear panels, Nakashima [11] tested six full-scale shear panels, showing that horizontal and vertical shear panels exhibited stable hysteresis and large energy dissipation capacity. Brando [2] later specifically investigated the effect of buckling inhibition of shear panels, and explained the mechanism of their better performance in terms of dissipated energy. In order to further explore the seismic behavior of steel plate, Driver [4] and Abolhassan [1] conducted their own cyclic tests on the steel plate shear wall system. Their test specimens demonstrated excellent ductility and energy dissipation characteristics, exhibiting stable behavior at very large deformations even after many load cycles. However, there were hardly any experiments on steel–concrete composite structural walls with bracings. Furthermore, most of research in the literature just gave general comments on the performance of steel composite shear walls, without deeper explorations about the effect of individual parameters.

In order to supplement the insufficient ongoing research on steel–concrete composite structural walls with bracings, especially that on inelastic behavior under reversed cyclic loadings, Guangxi University developed and tested four specimens consisting of one steel–concrete composite structural walls for control and other three ones with bracings. This paper covers a comprehensive research involving experimental and FE numerical investigations. First, the test program is introduced and then the observations of experiments are described in detail. A series of FE analyses including 54 cases is presented using a proven reliable tool DIANA [3] in terms of load–displacement relationship, secant

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stiffness and the energy dissipation capacity. Key parameters studied here are the shear span ratio, thickness of shaped steel and axial load ratio.

2. Test program

2.1. Details of specimens

The experimental program included a total of four specimens named SW-1, SW-2, SW-3 and SW-4, which represented a series of half-scale short-pier shear walls of common building. All specimens had the exactly same dimension as illustrated in Fig. 1. The specimen was designed and constructed following the code provisions of Chinese code GB 50010-2002. A size of 720 mm × 120 mm × 1300 mm was adopted for the wall, which was connected to a concrete head with the dimension of 920 mm × 400 mm × 400 mm. Four reinforcing bars with a diameter of 12 mm were used as vertical reinforcement, while the horizontal reinforcement was provided by reinforcing bars with a diameter of 6 mm at a spacing of 100 mm. There were embedded columns at two ends of walls which were reinforced with channel shaped steel and angle shaped steel. The reinforcement layout is shown in Fig. 2. The differences between each specimen were about flat shaped steel served as transverse reinforcement of the embedded column and "X" shaped steel bracings, which is demonstrated in Fig. 3. The control specimen SW-1 was constructed using flat shaped steel at a spacing of 200 mm in the embedded column but with no steel bracing. Specimens SW-2 and SW-3 differed with SW-1 in steel bracing, which had three and four layers of "X" shaped steel bracings in the wall respectively. Specimen SW4 had the same layers of steel bracing with SW-2 but the spacing of flat shaped steel in the embedded column was adjusted to 100 mm. The details of specimens were summarized in Table 1 and the comparison of reinforcement ratios of specimens were listed in Table 2.

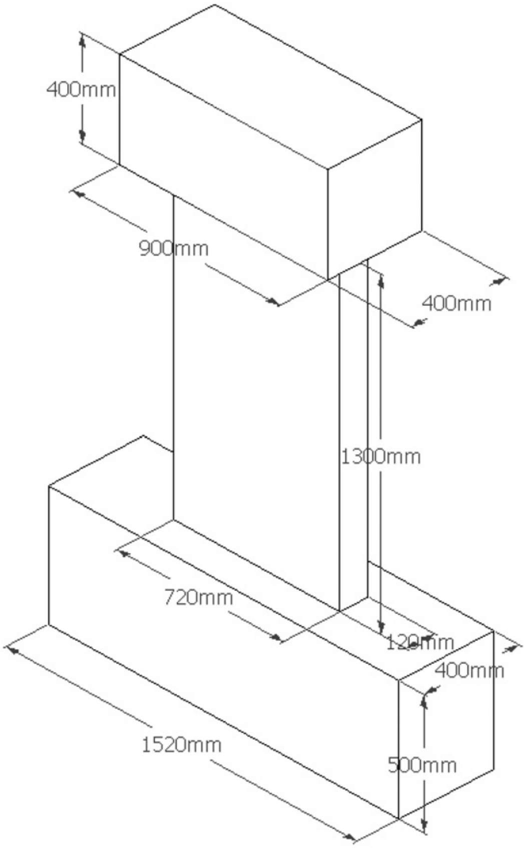

Fig. 1. Specimen dimension.

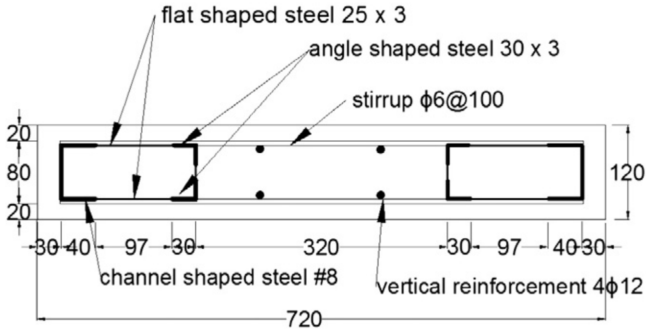

Fig. 2. Reinforcement layout.

2.2. Material properties

The concrete used for all specimens was of C35 with the average compressive strength calculated using the cube samples of 33.5 MPa. The longitudinal reinforcement used in the wall was 12 mm diameter deformed bars of HRB335, while the horizontal reinforcement employed was 6 mm diameter deformed bars of HPB300. Test results obtained from samples of 12 mm and 6 mm diameter bars indicated an average yield stress of 335 MPa and 326 MPa respectively. Three different kinds of shaped steel were adopted in this experiment, namely 8# channel steel, 30 × 3 angle steel and 25 × 3 flat steel. The relevant properties of concrete, reinforcing bars and shaped steel are listed below in Table 3.

2.3. Instrumentation

A sufficient number of measuring devices were used in the experimental tests to record the strains and deformations. Strain gauges were placed on both shaped steel and longitudinal reinforcements at selected locations within the walls. The lateral displacements of the top head were measured using displacement transducers, while a range of LVDTs was installed at the surface of walls to measure the flexural and shear deformations.

2.4. Test setup

Each of the test specimens was subjected to axial loads and quasi-static load reversals to simulate an earthquake scenario. A constant axial load of 721 kN ($0.3A_g f_c'$) will be applied by one hydraulic jack of 1000 kN loading capacity with its end connecting to the concrete head. A load cell will be attached to the jack to measure reaction force. The load transfer system consists of a steel beam, a steel spreader plate of 50 mm and several steel rollers, which can be seen from Fig. 4. This setup is designed to ensure uniform axial load distribution on the wall cross section area, and more importantly, to accommodate the horizontal movement of wall specimens due to lateral displacements.

A reversible horizontal load was applied to the concrete head by a double acting 2000 kN capacity electro hydraulic actuator. The loading history with applied cycles versus the displacement is shown in Fig. 5, which includes three stages: two before yielding and one after yielding. The first stage aiming to find the cracking displacement Δ_{cr} increases by the step of 2 mm. After cracking happening in both directions, the cycle continues by the same size of step until the yielding of steel is monitored. The post-yielding part of loading history has an increase of one yield displacement Δ_y every three cycles, and will be terminated when the specimen is deemed to have failed.

The bottom of the wall was connected to laboratory strong floor by prestressing rods, which aimed to prevent horizontal movement between wall base and the strong floor as well as the overturning