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Experimental and numerical investigation of jointed self-centering concrete walls with friction connectors

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A B S T R A C T

A jointed self-centering (SC) concrete wall system with friction connectors is proposed, in which the precast concrete wall panels are assembled through unbonded posttensioning (PT) tendons to provide self-centering capacity, and friction connectors at the vertical joint provide supplementary energy dissipation as the walls move relatively to each other during a major earthquake. The wall toes are protected by the steel jackets from crushing as the walls rock. The behavior of the jointed wall system was experimentally investigated through nine cyclic load tests, based on which the influence of different initial PT forces and friction forces on structural performance of the walls was discussed. Besides, strains on the steel jackets during the tests were measured to validate the effectiveness of steel jackets, and three-dimensional laser scanning technique was applied to measure the in-plane and out-of-plane deformations of the walls. It is observed that the main structure remained resilient after the nine tests with the maximum drift ratio of about 2.98%, though cracking in concrete cover at the eastern connectors was found after a number of reversal loading, which calls for improved structural details. A numerical simulation method of the jointed SC wall system is proposed, and the simulated hysteretic behaviors match well with the test results.

1. Introduction

Concrete structural walls are frequently used as the primary lateral load resisting system of reinforced concrete (RC) buildings, which provide a cost effective means to resist lateral seismic loads. Investigations on structural failure or damage in past major earthquakes, however, revealed that though buildings designed using conventional methods may survive after a major earthquake, excessive residual deformations often exist and result in enormous costs for post-event repair and additional downtime losses [1]. Among the efforts to improve the seismic resilience of buildings, the post-tensioned concrete wall systems have been developed, in which precast wall panels are usually field assembled using the unbonded posttensioning (PT) elements to provide the self-centering (SC) capacity. These precast PT concrete walls, as recommended in the PREcast Seismic Structural Systems (PRESSS) program, include the single and joint walls. The single walls have been studied both analytically [2,3] and experimentally [4–8], and they were also named as the “hybrid” walls due to the combined use of mild steel and high-strength unbounded PT steel. Reversal cyclic tests on 0.4-scale hybrid walls [9] showed desirable energy dissipation and ductile behavior, as well as superior restoring capacity over the emulative cast in-situ specimen.

The jointed precast wall system, on the other hand, usually consists of two or more single SC walls connected with each other through shear connectors along the vertical joints. These connectors dissipate seismic energy through inelastic deformations, and they are easier to be replaced as compared with the mild steel used in the single SC walls. Several connectors have been proposed, including the slotted flexural steel plates [10], the U-shape flexural steel plates developed in the PRESSS program [11] and the recent Oval-shape steel plates [12], etc. Henry et al. [13] recommended the use of the O-connector (i.e. the Oval-shape steel plate) based on their numerical and reversal-cyclic test results. A simplified analysis and design approaches were proposed by Aaleti and Sritharan [14] and Rahman and Sritharan [15], respectively, so as to characterize the unbonded PT precast wall system and promote its development.

Laboratory tests on these SC walls, however, showed different levels of concrete crushing at wall toes [6,16] as the walls rocked and high compressive stresses occurred, which may trigger the loss in PT forces and premature out-of-plane buckling of the walls. In addition, the energy dissipation was through metallic yielding so that the dissipators have to be replaced after a major earthquake.

Motivated by prior research, this paper proposes a jointed self-centering (SC) concrete wall system with friction connectors (FDs) to

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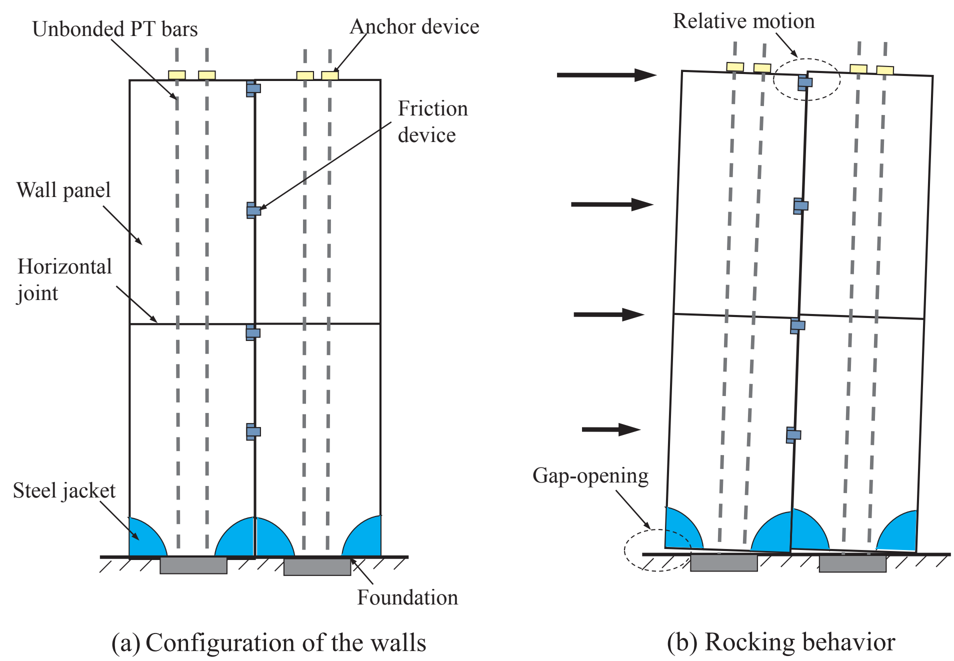

Fig. 1. Jointed SC walls with friction connectors.

realize adjustable and readily recoverable energy dissipation. In the proposed wall system, steel jackets at wall toes protect the concrete from crushing as the walls rock. Working principle of the proposed jointed SC walls is presented and the structural behavior was experimentally investigated through nine cyclic load tests. A numerical simulation method of the jointed SC wall system is proposed and validated through test results.

2. Jointed SC concrete walls with friction connectors

The configuration of the proposed jointed SC walls is illustrated in Fig. 1(a), where two single walls are connected at the vertical joint using friction connectors. Each wall usually consists of multiple precast concrete wall panels, which are precompressed by using the unbonded PT bars running vertically through the panels to the foundation. As the lateral loads become large enough, the walls rock and gap-opening occurs at the wall-foundation interface. As the walls move relatively, the friction connectors at the vertical wall joint transfer the horizontal loads and dissipate the energy through friction, as shown in Fig. 1(b). The friction connector consists of a slotted channel steel and two outer steel plates, as shown in Fig. 2(a) and (b). The channel steel is embedded in one wall, and the two steel plates are attached to the other wall through anchor bolts. The steel plates and channel steel are bolted together using friction bolts, and two friction plates are attached on the outer surfaces of the channel steel. Normal forces are usually applied to the friction bolts by using a torque wrench. The slot in channel steel allows the friction bolts moving along the slot for energy dissipation, as shown in Fig. 2(c). Steel jackets were placed at the wall toes and were precast in factory with the bottom wall panel, as shown in Fig. 2(d), and through-bolts are used in conjunction with the steel jacket to provide three-dimensional constraint to the in-filled concrete. As a result, the wall toes are protected from crushing as the walls rock. Similar to other SC systems using friction devices [17–19], the jointed wall system is expected to show a typical double flag-shape force-drift relationship [19].

3. Cyclic load tests of jointed SC concrete walls

3.1. Specimen descriptions

An experimental investigation on the behavior of jointed wall system under cyclic lateral loads was carried out at the Key Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education at Southeast University. Taking the wall on the left side of the wall system in Fig. 1(a) for example, as shown in Fig. 3, each wall panel had a thickness of 100 mm and a width of 950 mm. The base wall panel had a height of 2010 mm, while the upper panel with loading beam (200 mm wide and 350 mm high) had a height of 2190 mm, as shown in Fig. 4, where the upper panel and the loading beam were integrally cast. Each wall panel had two tendon ducts with a diameter of 30 mm. There were four connecting steel bars with a diameter of 12 mm embedded in the bottom of the top panel; accordingly, at the top of the bottom panel there were four embedded ducts with a diameter of 30 mm. The connecting bars were inserted into these ducts with bisphenol A epoxy resins when upper and base wall panels were assembled in laboratory, and epoxy resins were also used at the interface of base and upper panels, so that the two panels would work as a whole and there was no shear slip at the horizontal joints.

Fig. 4 further shows the structural details of the wall panels. The longitudinal and transversal reinforcing bars used the HRB400 steel with the nominal yield strength of 400 MPa. The tested yielding strength and ultimate were 467.5 MPa and 607.5 MPa, respectively, and the ratio of elongation was 23.5%. The steel reinforcements in base and top wall panels were the same. To prevent the damage in panel toes at the horizontal joints, eight steel angles were placed at the ends of horizontal joints (four of them were shown in Fig. 4). The steel angles had a thickness of 8 mm and equal leg lengths of 100 mm. Four steel jackets were fabricated using 8 mm thick plates and the quarter-round plates had a radius of 300 mm.

Fig. 5 illustrates the fiction connector adopted in the tests, which consisted of two steel plates and one slotted channel steel. All the three parts were made of 10 mm thick steel plates, except that the ring-like slot was manufactured by 1 mm thick iron sheet that was welded to the inner surfaces of the channel legs. Note that the channel steel was precast in the concrete wall, and the slot accommodated the friction bolts that passed across the wall. There were four holes on each steel