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Cyclic testing of unbonded post-tensioned concrete wall systems with and without supplemental damping

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ABSTRACT

A series of cyclic lateral-load tests were conducted on four different unbonded post-tensioned precast concrete wall systems, including two Single Rocking Walls (SRW) and two PREcast Wall with End Columns (PreWEC). The main purpose of these tests was to systematically investigate the cyclic response of post-tensioned concrete walls with varying amounts of supplemental damping while keeping the initial post-tensioning force, wall dimensions, and confinement details constant. A secondary objective was to validate the wall panel design including the appropriate selection of axial force ratio and design of confinement and armouring details. All of the test walls exhibited excellent performance with uplift and rocking at the wall base with only minor damage observed, consisting of small amounts of spalling in the wall toes. There were consistent observations and measurements of the wall damage, concrete compressive strains, and wall neutral axis depths for both the SRW and PreWEC systems with the same wall panel dimensions. Based on these observations it is concluded that the behaviour of the wall panel in a PreWEC system is independent of the number of energy dissipating O-connectors. The O-connectors increased the hysteretic energy dissipation in the wall system and provided between 1.1% and 1.4% of additional equivalent viscous damping per connector for the PreWEC walls tested. Overall, the behaviour of the four walls tested confirmed the design procedures used, with both the global force-displacement response and local response parameters predicted with sufficient accuracy using an existing simplified analysis method.

1. Introduction

Structural concrete walls provide strong, stiff, lateral-load resisting elements that can reduce lateral drifts during earthquakes. However, the plastic hinge regions in ductile reinforced concrete walls are subjected to large inelastic strain demands during earthquakes that result in significant structural damage. Recent earthquakes have highlighted the impact of damage caused to ductile reinforced concrete structures, which can result in large economic costs due to business down time, repairs, demolition, and rebuilding [1,2]. In an effort to control the damage in a structure to a certain performance level and isolate irreparable damage to easily replaceable components, engineers and researchers have developed low-damage seismic resisting systems. Low-damage seismic resisting wall systems can be designed using unbonded post-tensioned (PT) precast concrete panels. Inelastic demand in unbonded PT walls is accommodated through the opening and closing of an existing joint at the wall base, introducing a rocking mechanism. In addition to providing lateral strength to the wall, the unbonded PT tendons are designed to remain elastic during a design-level earthquake to provide a restoring force to minimise residual drifts.

The concept of connecting precast concrete elements together with unbonded PT was introduced during the PREcast Seismic Structural Systems (PRESSS) research program conducted in the 1990s [3]. During the PRESSS program a jointed wall system was developed that consists of two or more PT precast concrete panels connected by energy dissipating connectors. The jointed wall system was included in a five storey prototype building that was tested by Priestley et al. [3]. Following introduction of the PT wall concept, several researchers have investigated simple PT wall systems that consist of a single precast concrete panel with no additional energy dissipating connectors [4–6]. These PT only wall systems uplift and rock at the wall base with no significant material inelasticity and therefore result in low energy dissipation during cyclic loading. To improve the energy dissipation ability or

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seismic performance of the unbonded PT concrete walls, additional energy dissipating elements are often used. Researchers have investigated several configurations of unbonded PT concrete wall systems with different energy dissipating elements, such as the previously discussed jointed wall system. An alternative hybrid system was also developed that consists of a single precast concrete wall with a combination of unbonded PT and mild steel reinforcement at the wall-to-foundation interface. A number of researchers have experimentally investigated the hybrid system using either mild steel dissipaters [7–11] and/or viscous dampers [12]. Analytical investigations into hybrid walls with viscous damping, friction damping and hysteretic damping provided using mild steel have been reported [13–15]. A PT wall system that used precast hollowcore panels was also developed and tested for applications in warehouse buildings [16,17].

Recently a new rocking wall system that consists of a PREcast Wall with End Columns (PreWEC) was developed and experimentally validated [18]. The PreWEC system is a variation on the original jointed wall system, and uses a single precast concrete wall panel with two end columns that are each anchored to the foundation using unbonded PT. The wall is joined to the end columns with specially designed energy dissipating O-connectors developed for the PreWEC system [19]. As with other unbonded PT concrete wall systems, the wall and columns are designed to uplift and rock when a lateral load is applied, with the floor diaphragms connecting the wall and end columns in the horizontal plane. The uplift at the wall base results in a relative vertical displacement along the joint between the wall and end columns where the O-connectors are attached. As a result of this vertical displacement, the O-connectors undergo flexural yielding and dissipate seismic energy. The PreWEC system was developed to optimise the moment capacity of the jointed wall system by maximising the lever arm between the PT tendons and the wall compression block. Another advantage of the system is that the columns undergo relatively small uplift and can therefore be used to support the floor diaphragms and transfer gravity loads. Wall-to-floor connection alternatives for the PreWEC system are discussed separately in Henry et al. [20] and Sritharan et al. [18].

To better understand the behaviour of PreWEC walls, an experimental study of PT concrete wall systems was conducted. A total of four wall systems were considered, including two single unbonded PT only walls, referred to as Single Rocking Walls (SRW), and two PreWEC systems. The objective of these four wall tests was to systematically investigate the cyclic response of walls with varying amounts of supplemental damping in the form of energy dissipating O-connectors while keeping the initial post-tensioning, wall dimensions and confinement details constant. The wall tests also provided an opportunity to further validate the wall panel design, including the choice of axial force ratio and confinement details, and to compare the experimental results of the walls against an existing simplified analysis method used for the design of PT wall systems.

2. Experimental program

The experimental program consisted of pseudo-static cyclic testing of four walls, two SRWs and two PreWEC systems. The specimen dimensions and parameters were selected to represent a target range of typical multi-storey commercial buildings between two to eight stories high in a region with medium to high seismic hazard. The building typology utilised unbonded PT precast concrete walls as the primary lateral force resisting system, and further details of the scale and prototype building are published separately [21]. The design of the test walls followed the New Zealand Concrete Structures Standard (NZS 3101:2006) [22] and used the design method for PT concrete walls proposed by Aaleti and Sritharan [23]. The parameters of SRW-A and SRW-B were varied to investigate the behaviour of two different SRW systems with different geometry and initial post-tensioning force. PreWEC-A and PreWEC-B specimens were designed based on the addition of end columns and energy dissipating O-connectors to SRW-B. To isolate the influence of the number of O-connectors, all other parameters between SRW-B, PreWEC-A and PreWEC-B systems were kept constant. Two cyclic tests were performed on PreWEC-A which are referred to as PreWEC-A1 and PreWEC-A2.

2.1. Wall specifications

The dimensions, design parameters, and cross section of each test wall are provided in Table 1 and Fig. 1. SRW-A and SRW-B consisted of a precast concrete wall panel cast with ducts along the length for placement of the unbonded PT tendons. The wall panel used for SRW-A had a length, thickness and height of 1000 mm, 120 mm and 3000 mm, respectively, while the wall panel used for SRW-B had a length, thickness and height of 800 mm, 125 mm and 2860 mm, respectively. The PT tendons used for SRW-A were 15 mm diameter high strength bars and the PT tendons used for SRW-B, PreWEC-A, and PreWEC-B were 15.2 mm prestressing strand. The targeted initial prestress (f_{pi}) in the wall PT was 239 MPa ($0.24f_y$) for the SRW-A and 696 MPa ($0.45f_y$) for SRW-B, PreWEC-A, and PreWEC-B. The targeted initial prestress force was selected to maximise the wall moment capacity while keeping the axial force ratio ($AFR = (P + N)/A_g f'_c$) below 10% to ensure no significant crushing occurred in the wall compression toe [24]. The tendon configuration and initial prestress were designed to ensure that the tendon force did not exceed the yield strength of the strand until lateral drifts over 3% were reached. The measured AFR of each wall are given in Table 1.

The panels were reinforced with minimum horizontal reinforcement at 100 mm centres, minimum vertical reinforcement with the layout shown in Fig. 1, and with specially designed confinement reinforcement at the wall base spaced at 40 mm centres over a height of 200 mm up the wall, as shown in Fig. 2(a) and (b). The confinement reinforcement was designed for the wall toe using the confined concrete model described by Mander et al. [25] with the maximum expected compressive strain in the wall toe calculated using the simplified analysis method proposed by Aaleti and Sritharan [26]. To minimise damage to the wall base, an armoured wall detail and grout pocket were used, as recommended by previous testing [18]. A steel angle base frame constructed from $25 \times 25 \times 5$ mm equal angle was cast into each precast wall end for additional confinement and protection of the panel edge, as shown in Fig. 2(c). The wall panel was seated on a grout pad that was located within a shallow pocket in the foundation for confinement. The wall was embedded approximately 10 mm into the grout pocket to increase the sliding shear resistance. To limit the concrete compressive strains and spalling of cover concrete in the toe region, SRW-B, PreWEC-A and PreWEC-B had a foam strip across the width of the cover region (15 mm) glued at each wall end, as depicted in Fig. 2(d). It is important to note that use of the foam effectively shortens the length of the wall by 30–770 mm.

PreWEC-A and PreWEC-B consisted of identical precast concrete wall panels to SRW-B with the addition of two post-tensioned end columns constructed from concrete filled square steel hollow sections (SHS) with a width, length and thickness of $125 \times 125 \times 5$ mm. The targeted initial PT force of the columns was 220 kN per column using a 26 mm diameter stress-bar with an unbonded length of 3000 mm for all PreWEC tests. The targeted initial PT force in the columns was selected using the design procedure published by Aaleti and Sritharan [23]. The O-connectors were placed across the wall-to-column joint, welded to the SHS and steel plates embedded into the precast concrete wall panel.