SHAKE-TABLE TEST ON A LOW-DAMAGE CONCRETE WALL BUILDING: BUILDING DESIGN

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ABSTRACT

A system level shake-table test of a full-scale low-damage concrete wall building implementing state-of-art design concepts will be conducted on the multi-functional shake-table array at Tongji University as part of an ILEE-QuakeCoRE collaborative project. The 2-storey test building was designed with post-tensioned (PT) walls that provide the primary lateral-load resistance in both directions, in conjunction with a concrete moment frame predominantly resisting gravity loads. Different floor systems and wall-to-floor connections that have been implemented in constructed buildings in New Zealand were incorporated in the test building to investigate different design concepts and detailing. Level 1 consists of precast concrete double tees and a steel tray composite floor is used on level 2. Conventional wall-to-floor connections using a flexible link slab and isolating device-type wall-to-floor connections were designed in the longitudinal and transverse directions, respectively. A number of alternative energy dissipating devices were positioned at wall base or/and beam-column joints of the building. The test building will be subjected to a large number of tests, including different combinations of wall strength, energy dissipating elements, shaking direction, and ground motions. The tests will provide a rich dataset to verify design procedures and numerical models. The design of the test building is described in this paper.

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Shake-Table Test on a Low-Damage Concrete Wall Building: Building Design

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Introduction

The damage caused to conventional modern buildings during major earthquakes often leaves them requiring either costly repairs or demolition, as highlighted by the 2010/2011 Canterbury earthquakes in New Zealand \cite{1} and other large earthquakes worldwide. The increasing need to reduce damage and downtime of modern buildings has led to the development of a low-damage design philosophy, where the earthquake loads can be resisted with damage confined to easily replaceable components.

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A number of different low-damage technologies have been developed and implemented that are suitable for different structural systems and building applications. Post-tensioned (PT) structural system have been well developed using PT precast concrete components that behave in a jointed manner with replicable energy dissipating elements. Unboned PT wall systems consist of a precast concrete panel with unbonded PT tendons anchored between the top of the wall and the foundation. When subjected to a lateral force, the unbonded PT tendons elongate, with the strain evenly distributed along the length of the tendon. The evenly distributed elongation allows the tendons to be designed to remain elastic to provide a restoring force that can re-center the wall to its original position when the lateral force is removed. To improve the energy dissipation capacity and seismic performance, walls with unbonded PT bars are often coupled with supplementary energy dissipating devices, such as jointed wall systems developed during the PRESSS program [2], hybrid wall systems with either mild steel dissipaters [3, 4] or viscous dampers [5] located at the wall-to-foundation interface, and Precast Wall with End Columns (PreWEC) using special energy dissipating O-connectors [6].

Unbonded PT wall systems have been subject to numerous pseudo-static lateral load tests and dynamic shake table tests [5, 7] to understand their lateral-load response and their damping behavior to verify displacement based design procedures. In addition, the importance of the interactions between structural components in low-damage structures has been identified. The behavior of wall-to-floor connections in PT wall buildings has been investigated using numerical models [8] and innovative connectors have been tested that can isolate the floor from the vertical uplift of the wall while still maintaining a horizontal load path [9]. The two large-scale subassembly cyclic tests performed at the MAST laboratory in Minnesota [10] confirmed that significant deformations are induced in the floor when connected integrally with the wall and the use of an isolated wall-to-floor connection could successfully reduce out-of-plane floor deformations and resulted in a more predictable lateral-load response.

When considering the entire structure, two shake-table tests of buildings that incorporated PT walls have been conducted. A three-story building that incorporated hybrid PT walls and slotted wall-to-floor connectors were tested at the University of California San Diego [11]. The test primarily focused on the diaphragm response, but demonstrated good performance of the PT walls. In addition, two four story buildings were tested simultaneously on the E-defense shake-table [12] with one building using conventional RC walls and frames and the other implementing PT walls and frames. The floor was rigidly connected to the PT wall and experienced significant damage at the wall-to-floor interface. A numerical model developed for the PT wall building highlighted the importance of capturing the system-level interactions, including the in-plane and out-of-plane response of the floor [13,14]. The results from these two shake-table tests have been valuable in understanding system-level response of PT wall buildings.

Research into unbonded PT walls has led to the publication of design standards and guidelines [15-17]. Several buildings that incorporate PT wall systems have also been constructed in New Zealand [18, 19], including the southern-cross hospital building in Christchurch that survived the Canterbury earthquake sequence largely undamaged. Significant progress has been made on detailing practices following the construction of buildings in New Zealand. However, the design and detailing of previous test buildings was unique and did not cover the range of designs expected in implemented PT wall buildings. Additional tests are required to understand the system level
behavior and verify the new concepts of wall, floor, and frame systems, as well as wall-to-floor connections so that design guidance can be improved.

To verify the seismic response of a low-damage concrete wall building implementing state-of-art design concepts and practical construction details, a joint research project between the International Joint Research Laboratory of Earthquake Engineering (ILEE) and the New Zealand Centre for Earthquake Resilience (QuakeCoRE) was proposed. The project included a shake-table test of a two-story PT wall building. The test building incorporates state-of-art research and practice in the design and detailing. The test building has been designed and will shortly be constructed and tested at the ILEE multi-functional shake-table array located at the Jiading campus of Tongji University. The design of the test building is described in this paper and the numerical modelling of the test building is presented in a separate paper [20].

Description of Test Building

The test building is assumed to be used for general office purpose and is intended to be located in a high seismicity zone in Wellington, New Zealand. The seismic design level is classed with an Importance Level 2, as per NZS 1170.0 [21]. The building is assumed to be founded on Site Soil Class C (shallow soil) according to NZS 1170.5 [21], with a Z hazard factor of 0.4 and a return period factor (R) of 1.0 corresponded to the design level earthquake.

Building Overview

The two-story test building has plan dimensions of $5.4 \times 8.95$ m, as shown in Figure 1a. The total height of the building from foundation surface is 8 m with each story 4 m high. The building structural system consists of a perimeter frame and two exterior PT walls in both directions. The perimeter frame is designed to primarily carry gravity loads, but will provide lateral-load capacity during some test configurations. The four PT walls are designed to primarily resist seismic loads in both directions. Level 1 consists of long-span precast concrete double tees with an insitu concrete topping. A steel tray composite floor is used in level 2 in a short span configuration with steel decking as permanent formwork and a reinforced concrete topping. A secondary steel beam is aligned through the center of the floor to reduce the span of the composite floor. The floor plans for both level 1 and level 2 are shown in Figure 1b.

PT walls

The PT walls on Grid 1 and 2 are 2500 mm long and 150 mm thick, while the PT walls on Grid A and B are 2000 mm long and 150 mm thick. The cross sections of the PT walls are shown in Figure 2a and b. The PT walls in Grid 1 and 2 will be cast in two sections (one per level). For the horizontal panel joints, the reinforcement from the bottom panel is inserted into metal ducts in the panel above also passing through the level 1 beam, as shown in Figure 2c. All ducts are then filled with high strength grout. The wall panels on Grid A and B will be cast as a single two-story high panel.

The wall-to-foundation connection detailing will incorporate light armoring with different shear transfer mechanisms typical of that used in implemented buildings. The connection for the Grid 1 and 2 walls will utilize a grouted pocket and the Grid A and B walls will use a custom steel pocket.
shear dowel, as shown in Figure 3.

Figure 1. Test building

Figure 2. Cross sections and details of PT walls
Frames

The four corner columns are identical as the building is symmetrical. A total of 12 HD20 reinforcing bars are placed at the circumference of the column section. The columns will be cast in two sections (one per level). The beam-column joints are cast with the beams and the column reinforcement from the level 1 column passes through metal ducts in the joint and into the level 2 column. The joints and ducts will then be filled using high strength grout. The section of the column at different locations are shown in Figure 4a and beam-column joint illustration is shown in Figure 4b. The foundation-to-column connection is designed to act as a pin. The columns will be lightly armored and will be located into a grouted pocket with unstressed post-tensioning tendons at first level resisting column actions generated during earthquakes.
All the beams will be precast half-beams with the top section cast at the same time as the floor insitu concrete topping. An example of the section of the precast beam unit for Grid 1 level 2 is shown in Figure 5a. To overcome the shortcomings of traditional beam plastic hinges, slotted (non-tearing) beams will be used at frame joints. The inclusion of a slot adjacent to the column face allows seismic rotations to be accommodated by opening and closing of the slot with rotation centered at the top of the beam [22]. This eliminates beam elongation at the floor level in order to reduce floor damage. The bottom reinforcement is not anchored into the column and so the beams will act as pinned connections when no energy dissipating devices are installed at the beam-column joints. For some test configurations energy dissipating fuses will be included, as shown in Figure 5b with energy dissipation devices installed at the bottom edge of the slotted beam.

Figure 5. Cross sections and details of beams

**Floors**

The level 1 floor uses 300 mm deep precast prestressed double-tees with an 80 mm insitu concrete topping. The width of 1950 mm can be cut 450 mm from the standard double tee width of 2400 mm. The double-tee floors will use a flange supported seating, as shown in Figure 6. The seating width is estimated to be 100 mm in accordance with current recommendations and will utilize an appropriately designed hanger detail. Armoring of the support ledge will be considered to reduce the possibility of spalling to the support beam. ComFlor 60 produced in New Zealand will be used in the test building for level 2. The concrete slab is 130 mm thick and the seating width of steel tray composite floor is also 100 mm.

Figure 6. Seating details for double-tee floor
Wall-to-floor connections

One of the objectives is to verify practical construction details that are likely to be used in low-damage buildings, in particularly alternative wall-to-floor connection details. The building will utilize both flexible wall-to-floor connections in one direction and isolating wall-to-floor devices in the other direction to provide a comparison of their respective behavior.

Flexible wall-to-floor connection will be used in the long span direction for both level 1 and level 2. The wall-to-floor connections in both levels will be designed to be stiff enough to transfer in-plane diaphragm loads in the longitudinal direction while being flexible in the vertical direction to accommodate the uplift and rotation of the PT walls. For level 1, a 600 mm wide insitu edge slab using a timber infill strip (as per link slab requirements of NZS 3101) will be placed between the double-tee unit and the beam parallel to the wall, as shown in Figure 7a. For level 2, the flexibility comes from the composite floor itself as the steel tray is aligned in the short span direction and so will be flexible in the long span direction of the building.

Isolated wall-to-floor connections will be used in the short span direction for both levels. A steel tongue that is embedded in the beam will insert into a slot in the wall so that the lateral seismic force can be transferred to the PT wall through the steel tongue in bearing but the tongue is free to slide vertically in the slot to eliminate the displacement incompatibility as the wall uplifts and rotates. An example of the isolated wall-to-floor connection at level 2 is shown in Figure 7b.

![Figure 7. Seating details for double-tee floor](image)

Energy dissipation devices

Three types of energy dissipating components and devices will be used in the building, including conventional steel fuses or connectors [23], lead extrusion (HF2V) damper [24] and viscous fluid damper [5]. Broadly representative examples of the three energy dissipating devices from previous research are shown in Figure 8. The devices will be installed at PT wall base and beam-column joints. Universal connection points will be designed so that the devices can be quickly interchanged between tests. Different combinations of energy dissipating devices will be installed in the building to investigate the properties of different energy dissipating devices.
Summary

A system level shake-table test of a full-scale low-damage concrete wall building is currently underway. The test building used post-tensioned wall systems implementing state-of-art design concepts and practical construction details. The tests will provide a rich dataset to verify design procedures and numerical models.

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