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Case Study on the Performance of Conventional and Rocking Concrete Wall Buildings

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ABSTRACT

This paper presents ongoing research comparing the performance of rocking structural systems to conventional systems using a set of "real world" archetypes, based on multi-unit residential uses and office/lab uses. Conventional concrete shear walls are typically designed to develop a single "plastic hinge" near the base of the wall, where localized damage occurs during significant earthquake events. Damage is fundamental to the design philosophy in modern building codes and is deeply embedded into modern earthquake engineering practice. In contrast, rocking concrete walls provide an approach in which predefined rocking interfaces (e.g., at the base) enable the wall to uplift/rock. This rocking is often controlled by a combination of post-tensioned steel and energy dissipating elements that enable inelastic response with less damage than conventional walls. In the conventional wall, the hysteretic shape is often larger at the beginning but then starts to pinch and lose strength after cycling. Rocking walls typically exhibit "flag-shaped" hysteric behavior, where the strength is maintained during cycling at the cost of less energy dissipation and, potentially, higher drift demands. The archetype design space is introduced and a case study illustrating performance differences is provided, including a brief discussion on design considerations to ensure a desirable failure mechanism.

Introduction

Low damage rocking systems have been developed over the course of the past several decades, giving engineers new tools to create enhanced seismic performance. The general idea of rocking walls is that a plastic hinge mechanism, with full hysteresis loops, is replaced by a rocking interface which typically has post-tensioning (PT) steel and energy dissipating (ED) elements that produce a "flag-shaped" hysteresis. The former dissipates energy by cracking in the concrete and yielding of the reinforcement over a plastic hinge height, typically within one or two stories. After significant cycling, pinching and strength degradation is often observed. In contrast, the latter dissipates less energy, but much of the nonlinear behavior is recoverable through recentering that occurs due to rocking and resistance provided by the PT bars and the gravity loads acting on the walls. Notably in the latter, the damage is constrained to the ED elements; thus, for the idealized

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scenario, less damage will occur in a rocking wall than in a comparable conventional wall.

Motivated by the above observations, this paper gives a brief introduction into the development of a suite of archetype buildings that were designed to explore the cost and benefits of low damage rocking wall buildings. To compare, each respective building was first designed with conventional concrete shear walls and then redesigned with post-tensioned concrete rocking walls. Two types of occupancies were considered: residential and office/laboratory. The archetypes are purposely realistic, reflecting architectural programmatic demands. Preliminary results are presented for an 8-story residential building, illustrating the performance differences between the conventional and rocking wall buildings. Additionally, a brief discussion is given on failure mechanism considerations in the design of rocking walls and the approach taken to mitigate undesirable, nonductile mechanisms.

Archetypes

The archetype buildings are designed for construction in downtown Los Angeles, CA, with 1-sec, S_1, and short period, S_s, spectral acceleration values of 0.72 g and 2.26 g, respectively. The buildings were designed to meet the requirements of the American Society of Engineers (ASCE) 7-22 standard [1], the American Concrete Institute (ACI) 318-19 standard [2], and ACI 550.7-19 standard [3]. The general floor plan is illustrated in Fig. 1 for the residential building, with a focus on the 8-story.

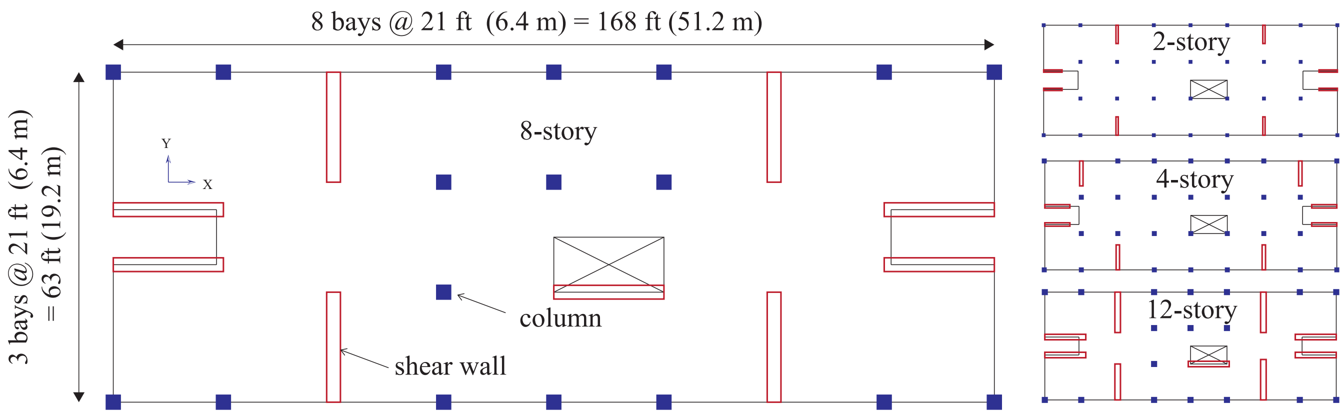

Figure 1. Typical plan view of residential archetype building designs.

Four building heights were designed for each occupancy type: 2, 4, 8, and 12 story. For the residential building, the first story is 15 ft (4.6 m) and all other stories are 10 ft (3.0 m). The footprint of the residential building is 170 ft by 65 ft (51 m x 20 m), including a 1 ft (30 cm) slab overhang.

Fig. 2 gives examples of the typical layout of steel reinforcement for the conventional and rocking walls and Table 1 gives reinforcing bar sizes for the 8-story conventional wall design. For the rocking walls, only the PT and ED bars (shown in black in Fig. 2(b)) extend into the foundation, enabling rocking at the wall-foundation interface. The boundary and web bars (shown in light gray in Fig. 2(b)) terminate just above the foundation. At the base of the wall, the wall ends (toes) are armored with steel plates to preclude toe crushing. Complete details of the archetype design suite, including the office/laboratory buildings, are planned to be published in a forthcoming National Institute of Standards and Technology technical note.

Analysis Model and Preliminary Results

A nonlinear building model is created in OpenSees [4]. The walls are modeled with displacement-based beam-column elements with a fiber-based cross-sections. Fiber sections are composed of nonlinear confined and unconfined concrete and reinforcing steel fibers. The behavior of the conventional wall models was calibrated against physical tests of walls [5]. For the rocking wall, corotational trusses are included to model the PT tendons and ED bars. Material regularization was conducted to obtain mesh-independent results. The shear response was not included in the model given they were capacity designed to avoid shear yielding.

a) conventional

b) rocking

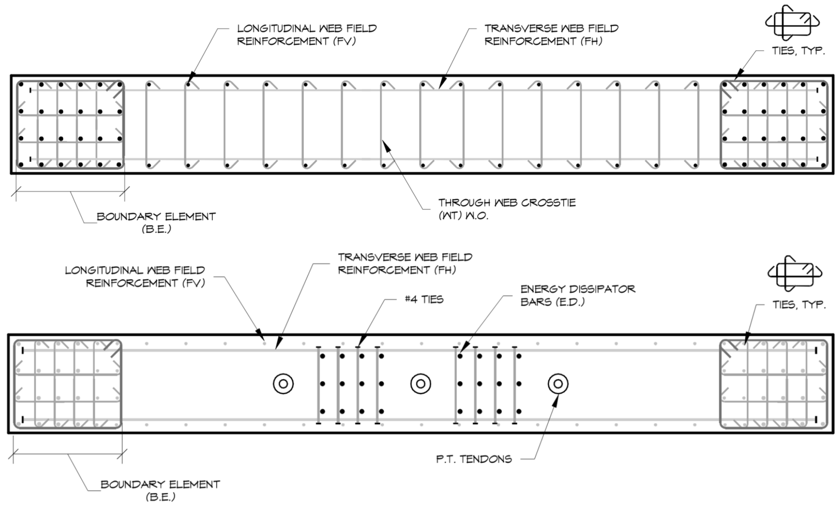

Figure 2. Base-level sections showing reinforcement details of a) conventional walls and b) rocking walls.

Table 1. Reinforcing bar details for the 8-story conventional wall design

<table>
<tr><th rowspan="3">Direction</th><th rowspan="3">Stories</th><th colspan="4">Boundary</th><th colspan="4">Web</th></tr>
<tr><th colspan="2">Longitudinal</th><th colspan="2">Transverse</th><th colspan="2">Longitudinal</th><th colspan="2">Transverse</th></tr>
<tr><th>Quantity</th><th>d_b, in</th><th>d_b, in</th><th>s, in</th><th>d_b, in</th><th>s, in</th><th>d_b, in</th><th>s, in</th></tr>
<tr><td rowspan="4">X</td><td>7-8</td><td>12</td><td>0.875</td><td rowspan="4">0.625</td><td rowspan="3">6.0</td><td rowspan="2">0.875</td><td rowspan="4">12</td><td rowspan="3">0.750</td><td rowspan="4">9</td></tr>
<tr><td>5-6</td><td>20</td><td>1.00</td></tr>
<tr><td>3-4</td><td>20</td><td rowspan="2">1.27</td><td rowspan="2">1.00</td></tr>
<tr><td>1-2</td><td>20</td><td>3.5</td><td>0.875</td></tr>
<tr><td rowspan="4">Y</td><td>7-8</td><td>16</td><td>0.875</td><td rowspan="4">0.625</td><td rowspan="3">6.0</td><td rowspan="2">0.875</td><td rowspan="4">12</td><td rowspan="2">0.750</td><td rowspan="4">9</td></tr>
<tr><td>5-6</td><td>24</td><td>1.00</td></tr>
<tr><td>3-4</td><td>24</td><td>1.27</td><td rowspan="2">1.00</td><td>0.875</td></tr>
<tr><td>1-2</td><td>24</td><td>1.41</td><td>3.0</td><td>1.00</td></tr>
</table>

d_b = bar diameter, s = spacing, 1 inch (in) = 2.54 cm

To illustrate the preliminary results, the 8-story residential building is subjected to a suite of 50 ground motions scaled to the uniform hazard spectrum with a 2475-year return period as shown in Fig. 3(a). The record set was chosen from the Pacific Earthquake Engineering Research (PEER) next-generation attenuation (NGA)-west database [6]. Fig. 3(b) shows the median results of the drift in the X-direction for the conventional wall building and the rocking wall building response (peak in black, residual in red). Peak drifts for the rocking and conventional walls are approximately 20 % higher in the upper stories and approximately 100 % higher in the first story due to the rocking interface. It is expected the peak drifts in the rocking wall building would be closer to the conventional wall building if the designs were revised to have similar base shear strength.

In contrast, the residual drifts are smaller for the rocking wall due to the recentering behavior. Residual drifts can be difficult to accurately capture in general [7] and in particular for fiber models (potential underprediction) [8], but the trend is informative, nonetheless. There is a clear benefit to having a building that has limited residual drift after a major earthquake; significant permanent drift would likely require structural repair or even complete demolition.

Fig. 3(c) shows the pushover curves for the 8-story residential buildings, including rocking walls with and without toe armoring (steel plates at the bottom corner). The strength of the conventional walls (designed per

ACI 318) is approximately 10 % higher than the rocking walls (designed per ACI 550.7). Both the conventional and armored rocking wall behavior is controlled by the reinforcing steel fracture, with the conventional walls losing strength at a smaller drift level than their rocking counterparts. The post-elastic stiffness is similar until approximately 2 % drift, which is the design level targeted to allow the PT to yield in the rocking wall.

The effects of toe armoring, and the associated details of how to terminate the compression steel at the rocking interface, are demonstrated in Fig. 3(c). The black (solid) line and red (dashed) line show the behavior assuming full armoring (plates on the base and sides of the toe) and base-only armoring (plate only on the base of the toe), respectively. For both these cases we assume the compression steel is attached to the base plate and therefore is modeled as fully developed. In contrast, the blue (dash-dot) line shows the behavior if we do not model the compression steel (assuming no base plate present). The unconfined concrete crushes, and the wall quickly loses strength. The key is ensuring the compression steel fully develops and does not buckle. Therefore, confinement (via armoring) of the toe ensures superior performance and damage avoidance for this critical area of the rocking wall. It is expected that, under certain design conditions, rocking walls satisfying ACI 550.7 may be more susceptible to compression failure than comparable conventional walls because the quantity of reinforcement resisting bending at the rocking interface, and the resulting tension-compression force couple, will typically be larger due to the placement of PT and ED bars near the center of the wall (Fig. 2(b)). This is an important consideration when designing rocking walls, and these preliminary results suggest that it may be important to revisit ACI 550.7 criteria to mitigate against this nonductile failure mechanism.

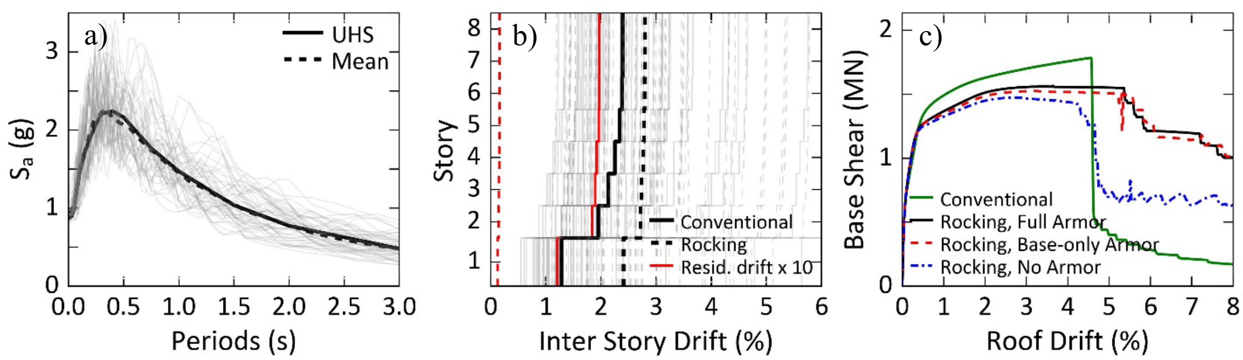

Figure 3. 8-story residential building, in the X-direction: (a) response spectra of the 50 input records, (b) median of the peak interstory drift (black) and residual drift (×10, red), and (c) pushover curves of the conventional, rocking, and un-armored rocking wall

Conclusions

A set of archetype buildings were designed to study the performance benefits of low damage rocking walls. The performance enhancements of rocking walls are demonstrated in the pushover analysis, with rocking walls demonstrating their ability to maintain strength at higher drift demands than conventional walls. The nonlinear response history results suggest the rocking wall building will drift approximately 20 % more than the conventional wall building, but the rocking wall building will have reduced residual drifts. The results also illustrate the need to clearly detail the toe to ensure confinement, prevent concrete crushing, and develop the compression steel. This can be achieved via toe armoring, which helps ensure the failure is driven by steel fracture in contrast to the unarmored walls that are susceptible to concrete crushing and bar buckling. The limited results indicate the need to revisit ACI 550.7 provisions to prevent nonductile compression mechanisms that can develop in rocking walls due to the larger compression demands imposed on the wall sections as compared to conventional walls. Further investigation is needed to understand the impact on strength, stiffness, and deformation capacity by including gravity framing system and soil structure interaction in the analyses. Additionally, investigating the benefits of rocking wall buildings in different seismic environments (e.g., Pacific Northwest) may be informative.

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