EARTHQUAKE-RESISTANT DESIGN OF UNBONDED PRECAST WALL SYSTEMS

M. Nazari¹ and S. Sritharan²

ABSTRACT

Precast concrete wall systems can be designed to rock at the base and produce low damage while resisting earthquake lateral forces. The simplest form of this system comprises of a precast concrete wall with unbonded Post-Tensioning (PT) tendons that are usually designed to remain elastic while the wall rocks on top of the foundation and elongates the tendon. Although negligible residual drift and low damage are associated with these Single Rocking Walls (SRWs), they possess low amount of energy dissipation due to elastic characteristics dominating their response. To overcome this limitation, supplementary hysteretic dampers can be added to increase the total damping of the system. Using easily replaceable Oval-shaped (O-) steel connectors to join the Precast Wall panel to two End Columns, PreWEC systems were developed to cost-effectively increase the hysteretic damping capacity in a rocking wall configuration. Shake table test investigations of SRWs and PreWEC systems, however, showed that both systems can be designed to produce dependable seismic response although SRWs do not possess the minimum amount of damping prescribed in existing design standards. The scope of this paper is to demonstrate how seismic design of both types of wall systems can be accomplished using force-based (FBD) and direct displacement-based (DDBD) methods. To accomplish this goal, results from a series of shake table tests on four SRWs and four PreWECs subjected to design-level and maximum considered earthquakes were used to estimate energy dissipation and strength Reduction (R-) factors of the test units to determine their corresponding design shear forces. Results indicated a constant R-factor of 3.5 for SRWs and larger values for PreWECs, depending on the amount of the damping in the system. Using example design problems and subsequent analyses, it is shown that the proposed design methods are appropriate for use in design practice.

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Introduction

In the most recent earthquakes, Cast-In-Place (CIP) concrete walls resulted in severe damage in the structures and consequent economic losses. Precast wall systems with unbonded post-tensioning connections are one of the seismic-resilient alternatives in concrete structures. Initiating with the idea of constructing seismic resilient precast structures in early 2000 [1], unbonded Post-

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Tensioning (PT) tendons were used to tie precast concrete walls to the foundation. When subjected to a lateral load, this connection allows for opening of mainly a single horizontal crack at the wall base and elongation of the PT tendons. As these Single Rocking Walls (SRWs) rock on top of the foundation under design-level earthquakes, the tendons will remain elastic enabling re-centering capability for the system. The concept of using rocking walls in concrete structures was analytically studied by Kurama et al. [2] to investigate the seismic performance of such systems when subjected to earthquake loading. Perez et al. [3] conducted quasi-static testing on a series of walls to understand their cyclic behavior during dynamic loading. Although the results from these tests revealed satisfactory lateral load performance of SRWs, the application of these walls in high seismic regions has not considered possible, due to their low energy dissipation capacity, which is provided through the inherent viscous damping, insignificant hysteretic damping of SRWs due to nonlinearity of concrete, and impacts of the wall on top of the foundation. Due to this fact, special energy dissipating elements were added to precast walls in order to provide additional hysteretic damping during rocking of the walls (e.g., [1, 4-5]). Precast Wall with End Columns, known as the PreWEC, is one such system developed by Sritharan et al. [5] by using a set of easily replaceable steel Oval-shaped connectors, namely O-connectors. These special energy dissipating elements, which join the wall panel to two end columns, undergo the flexural yielding as the system rocks.

Marriot et al. and Twigden et al. [6, 7] separately conducted shake table tests on a series of SRWs and wall systems with external dampers, including PreWECs [7], and these systems were subjected to a series of near-field and far-field design-level earthquakes. The researchers showed that the wall systems satisfactorily responded during major events; however, different energy dissipation components of the rocking wall systems as well as proper procedures to determine seismic design forces following the U.S. codes [8] were not addressed in these studies.

ACI ITG-5.1 [9]—one of the existing building standards for designing precast wall systems—recommends a strength Reduction (R-) factor of five, similar to that of CIP concrete walls, to estimate the seismic design force of rocking wall systems, following an FBD approach. Because of a lower damping capacity of SRWs than that of CIP walls and a variable amount of damping provided in PreWECs by way of using a specific number of O-connectors, this methodology will not be efficient for designing these precast wall systems. To overcome the aforementioned deficiencies, a shake table investigation was undertaken on eight rocking wall systems, four SRWs and four PreWECs, which were designed with different key design variables, including the initial prestress force, base moment-to-base-shear ratio, and external hysteretic damping. Using the Network for Earthquake Engineering Simulation (NEES) shake table facility of the University of Nevada at Reno (UNR), the test walls were subjected to a set of ground motions representing different seismic hazard levels. The collected data from these tests were used to: (i) evaluate the multiple-level performance of the rocking systems during different intensities of earthquakes, (ii) quantify individual damping components in each system, and (iii) establish appropriate R-factors that may be used for a force-based design of these precast wall systems following the current U.S. codes [8]. In this paper, the proposed design method is presented and verified using example design problems, subsequent dynamic analyses during a set of design-level ground motions, and a performance-based assessment procedure.
Summary of Experimental Program

Table 1 summarizes the base shear resistance of four SRWs and four PreWECs, which is in the range of 23.4 to 83.6 kips. Lateral resistance of the test units were achieved following the Simplified Analysis (SA) method as explained in Aaleti and Sritharan [10]. In this method, the required area of tendons is determined based on moment equilibrium of forces acting on the wall base, using an equivalent stress block and a tri-linear approximation for estimating the neutral axis depth variation as a function of wall base rotation. Among these test units, SRW2 and PreWEC-2 were designed to represent a 5/18 scale of a rocking wall system designed for a six-story prototype office building; this prototype building followed the current design codes (i.e., [8]) for a location in Los Angeles, California. The shake table test utilized different types of earthquake excitations (e.g., Near-Field (NF) vs. Far-Field (FF) and long-duration vs. short-duration), representing four seismic hazard levels of EQ-I to EQ-IV. EQ-III and EQ-IV levels respectively represent design-based (DBE) and maximum considered (MCE) earthquake events. Fig. 1 presents the experimental setup used for the shake table investigation at UNR. As shown in this figure, the inertia force generated due to the seismic load was applied to the test unit by an external mass-rig system used in the test setup. More details of the experimental setup, ground motion scaling, and instrumentation scheme can be found in Nazari et al [11, 12].

A summary of the experimental results is presented in Table 1. This table entails the estimated equivalent viscous damping ratio of the test walls at 2% design drift as well as their maximum response ratios in terms of the maximum transient drift, maximum absolute acceleration, and residual drift, during EQ-III and EQ-IV hazard level motions normalized by the corresponding allowable limits. These limits are defined based on the recommendations of Rahman and Sritharan [13] for different intensities of ground motions. As explained in Nazari et al. [12], the equivalent damping of the test units were defined to represent their different energy dissipation components, including the inherent elastic viscous damping in the system, hysteretic damping due to inelastic deformations of O-connectors as well as concrete nonlinearity at wall toes, and the energy loss during impacts. The total damping ratio of the test units varied from 5.5 to 16.3% for SRWs and PreWECs depending on the number of O-connectors. Following a DDBD design methodology, results from this shake table study confirmed satisfactory response of the test
units in terms of the maximum drift during DBE motions when shear forces corresponding to their energy dissipation capacity are used (e.g., SRW3 and PreWEC-s1). The outcomes of the displacement-based study were also used to establish appropriate R-factors that may be used for a FBD method. This is explained in the following section.

Table 1. Test matrix and summary of experimental results

<table>
<thead>
<tr>
<th>Wall system ID</th>
<th>$V_{2%}^*$ (kips)</th>
<th>Equivalent viscous damping ratio (%)</th>
<th>Maximum response ratio** (drift, absolute acceleration, residual drift)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hysteretic and viscous at 2% drift</td>
<td>Impact</td>
</tr>
<tr>
<td>SRW1</td>
<td>23.4</td>
<td>4.5</td>
<td>1.3</td>
</tr>
<tr>
<td>SRW2</td>
<td>42.0</td>
<td>3.5</td>
<td>1.9</td>
</tr>
<tr>
<td>SRW3</td>
<td>66.8</td>
<td>7.1</td>
<td>1.7</td>
</tr>
<tr>
<td>SRW4</td>
<td>80.5</td>
<td>4.4</td>
<td>1.1</td>
</tr>
<tr>
<td>PreWEC-1</td>
<td>83.6</td>
<td>14.6</td>
<td>1.5</td>
</tr>
<tr>
<td>PreWEC-2</td>
<td>41.1</td>
<td>14.3</td>
<td>0.8</td>
</tr>
<tr>
<td>PreWEC-s1</td>
<td>70.1</td>
<td>7.7</td>
<td>2.0</td>
</tr>
<tr>
<td>PreWEC-s2</td>
<td>57.1</td>
<td>14.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>

* Shear resistance at 2% drift, using the Simplified Analysis (SA) method [10].
** Ratio between the maximum recorded responses and the corresponding allowable limits, which are (0.4%, 0.954g, 0.1%), (1.2%, 2.117g, 0.3%), (2%, 4.32g, 0.5%), and (3%, 6.48g, 0.75%), respectively, for EQ-I through EQ-IV levels of input motions [13].

Proposed Equations for Damping Ratios and R-Factors

Consistent with recommendations in the current design codes [8], Eqs. 1 and 2 are presented to estimate the R-factors for seismic design of rocking wall systems with different damping capacities. These equations were derived by estimating the base shear forces corresponding to the elastic response of the system ($V_e$) and design-level ($V_d$), respectively, calculated from the FBD (i.e., ASCE 7-10 [8] with R-factor=1) and DDBD (using total equivalent viscous damping ratio of $\xi_{eq}$) procedures. Using these equations for seismic design of rocking wall systems for the FF and NF ground motions will lead to design of buildings that are capable of achieving the basic seismic performance objectives [14].

$$ R = 0.46 \times \xi_{eq} + 0.93 \; ; \; \text{FF records} \quad (1) $$

$$ R = 0.15 \times \xi_{eq} + 2.65 \; ; \; \text{NF records} \quad (2) $$

As outlined through this shake table study, $\xi_{eq}$ at design drift level mainly consisted of the energy dissipation due to hysteretic action of O-connectors. Nazari et al. [15] suggested Eq. 3 to correlate this damping component with the response characteristics of the O-connectors and shear capacity of the wall system.

$$ \xi_{hys,D\%} = \frac{\Delta_{C_y,C}}{\pi \times V_{D\%} \times H_s} $$

(3)
where, $N_{\text{conn.}}$ = total number of connectors, $V_{D\%}$ = shear resistance of the PreWEC system at $D\%$ drift ratio, $H_s$ = seismic height, $F_{c,\text{ave}}$ = average of connector forces at yield and $D\%$ drift ratio of the system, $\Delta_{c,y}$ = yield displacement of the connectors, and $l_{con}$ = location of the connectors measured from the point of rotation of the wall panel [15].

In addition to this damping term, additional damping ratio of 4.2% due to the material nonlinearity of concrete at wall toes and inherent viscous damping of the system will be added to the results of Eq. 3, as well as, 1% and 1.5% damping due to impacts for PreWECs and SRWs, respectively. According to Eq. 1, SRWs could be designed with an R-factor of about 3.5 for FF records, regardless of their limited damping ratio of less than 6% [12]. Although PreWECs may appear to be more expensive due to the use of end columns and O-connectors, these systems can be designed to be competitive with SRWs because of their lower design base shear forces compared to SRWs, due to high damping.

**Analytical Model and the Case Study Buildings**

To verify the accuracy of the proposed equations for force-based design of rocking wall systems, a set of case study buildings was designed with a variety of SRWs and PreWECs with the R-factors as derived from Eqs. 1 and 2. In this paper, results from dynamic analysis of a six-story building designed with different numbers and configurations of rocking walls, as lateral load resisting elements, are presented. Two of these case study buildings used PreWECs with different total damping ratios of $\xi_{eq}$ (namely, PreWEC6-$\xi_{eq}$) and the third one was designed with SRWs (namely SRW6). The case study buildings were then subjected to a set of FF earthquake records, as presented in FEMA P695 [16]; these motions were scaled according to SEAOC guideline [14] to represent DBE earthquakes. An experimentally verified analytical model was used in this study for the purpose of dynamic analysis [12, 15].

**Properties of the Case Study Buildings and Selected Ground Motions**

The plan view of the six-story case study buildings using PreWECs is shown in Fig. 2a. According to this figure, three PreWEC systems were used as the lateral load resisting elements of the building in the transverse direction. In the longitudinal direction of the building, moment resisting frames were used to resist the earthquake loads. For the building with SRWs, four walls were considered for design of the building in the transverse direction. The buildings are located in San Diego, CA.

Different amounts of damping ($\xi_{eq}$) were provided for buildings with PreWECs; in this study, 13% and 18% damping ratios were selected for PreWEC6-13 and PreWEC6-18 case study buildings, with the corresponding R-factors of 7 and 9.3, as derived from Eq. 1. Table 2 presents the design details of wall panels, end columns, and O-connectors. As summarized in this table, different types and numbers of O-connectors were used for PreWEC6-13 and PreWEC6-18 buildings to join the wall panel with either of the end columns. These buildings were subjected to a total of 10 FF earthquakes corresponding to site class C (according to the location of the building), which were scaled to represent EQ-III seismic hazard level, representing DBE events [14]. Fig. 2b presents the acceleration response spectra of the scaled records.
Figure 2. Properties of the case study buildings and scaled ground motions

Table 2. Design parameters for the case study buildings

<table>
<thead>
<tr>
<th>Building ID</th>
<th>R-Factor/No. of walls</th>
<th>Design force/wall (kips)</th>
<th>Area of PT tendon (in²) / Initial PT stress</th>
<th>Type-number of connectors*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRW6</td>
<td>3.7/4</td>
<td>583</td>
<td>13.6 / 0.65$f_{pu}$**</td>
<td>-</td>
</tr>
<tr>
<td>PreWEC6-13</td>
<td>7.0/3</td>
<td>387</td>
<td>7.4 / 0.7$f_{pu}$</td>
<td>2.8 / 0.8$f_{pu}$</td>
</tr>
<tr>
<td>PreWEC6-18</td>
<td>9.3/3</td>
<td>281</td>
<td>1.9 / 0.68$f_{pu}$</td>
<td>3.0 / 0.8$f_{pu}$</td>
</tr>
</tbody>
</table>

* per joint; connectors A and B have, respectively, yielding and ultimate force and deformation properties of
A-yield (17kip, 0.25in.), A-ult. (18kip, 4in.), B-yield (17kip, 0.1in.), and B-ult. (18kip, 4in.).

** $f_{pu}$ = tensile strength of tendon = 270ksi.

Experimentally Verified Analytical Model

An experimentally validated simplified analytical model was generated in OpenSees [17] and used to estimate the maximum responses of the buildings. Fig. 3 shows the model for PreWEC systems; when the PreWEC model is subjected to a lateral deformation, two base rotational springs in parallel would be activated simultaneously, allowing the total moment resistance and energy dissipation of the system to be captured. Response of SRWs is achieved by modeling only the first rotational spring, as shown in Fig. 3a. More information about this model and its verification can be found in Nazari et al. [12, 15].

Verification of Proposed R-Factors for Design of Precast Wall Systems

Using the analytical model, maximum responses of the case study buildings in terms of the maximum transient drift were calculated and compared with the allowable limit of 2%, as suggested by Rahman and Sritharan [13] for design-level intensity of ground motions. This ratio is plotted in Fig. 4a for six story buildings during FF design-level ground motions. A value of below one for the ratio indicates the satisfactory drift response of the buildings. As shown in this figure, the proposed design approach led to satisfactory performance of rocking systems in terms of the maximum drift with generally sufficient margin of safety with respect to the selected
permissible limit. Fig. 4b shows the effect of additional hysteretic damping provided in PreWEC systems on their drift time history response during a DBE record. As shown in this figure, addition of O-connectors in the rocking walls resulted in slight reduction in the maximum drift as well as faster decay of dynamic response.

![Diagram of Seismic Mass and Seismic Height](image)

**a)** Two-spring SDOF model  
**b)** Moment resistance provided by each spring  

**Figure 3.** Experimentally verified OpenSees model for a PreWEC system

![Graph of Maximum Drift Ratio](image)

**a)** Ratio of the maximum demand to the allowable limit of 2% for DBE records  
**b)** Impact of additional hysteretic damping on the drift time history response during FRIULI/A-TMZ000 record [16]

**Figure 4.** Maximum and time history drift response of case study buildings during DBE records

**Conclusions**

An analytical parametric study was conducted in this paper to verify a set of new strength Reduction (or R-) factors suggested for designing precast concrete rocking walls both with and without additional hysteretic damping. Using an experimentally validated OpenSees model, six-story case study buildings with identical plan views and different numbers and configurations of rocking wall systems (i.e., SRW and PreWEC with 13% and 18% damping ratios) were subjected
to a set of scaled far-field ground motions representing the design-level events. Using the dynamic
analysis results and criteria established for performance-based seismic evaluation of rocking walls,
it was shown that the seismic performance of the rocking structures designed with the new sets of
R-factors satisfied the performance limits of the maximum lateral drift for design-level far-field
earthquake motions. It is also concluded that PreWECs with larger hysteretic damping generally
experienced lower maximum drifts, with sufficient margin of safety with respect to the permissible
limit, and faster decay of dynamic response. SRWs with the low amount of energy dissipation
capacity responded satisfactorily when designed with the recommended R-factor.

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