SELF-CENTERING PENDULUM SHEAR WALLS VIA NONLINEAR ELASTIC KINEMATICS

P.F. Silva[(1)], J. Dunne [(2)], R. Burgueño[(3)]

[(1)] *Associate Professor, George Washington University, silvap@gwu.edu*
[(2)] *Graduate Research Student, George Washington University, juliadunne@gwmail.gwu.edu*
[(3)] *Professor and Chair, Stony Brook University, Rigoberto.Burgueno@stonybrook.edu*

Abstract

One of the main challenges in structural engineering is nowadays the development of structural design concepts that can be used in the built infrastructure towards achieving immediate occupancy and minimum economic losses following an extreme seismic event. Research on unbonded post-tensioned shear walls (UPSW) has clearly demonstrated that these systems fit well within this grand challenge because of their self-centering response under earthquakes. Research has clearly substantiated the superior self-centering performance of UPSWs when compared to monolithic cast-in-place concrete walls, that they are nowadays accepted as viable lateral force resisting elements. Yet, these UPSWs have not been adopted extensively in the built infrastructure and the following critical issues need to be further resolved: concrete crushing at the wall toes, yielding of tendons, wall walking, and energy dissipation from ductile connectors that must be replaced and can lead to permanent deformations after an extreme hazard. Notably, combination of these issues requires setting strict drift limits to preserve the self-centering capabilities of UPSWs.

Building on the assets of UPSWs, this research proposes a new method of designing UPSWs that can improve, or eliminate, many of the above noted technical issues. This is achieved by incorporating the following synergistic concepts: (1) At the footing interface the wall geometry consists of circular profile, and (2) use multistable elastic devices as vertical shear connectors. In the concept investigated in this research the superior performance of being damage-free and self-centering under lateral loads are maintained; but in addition, system kinematics are optimized to increase the system's energy dissipation capacity. This new system is designated as a pendulum UPSW system because, instead of rocking about the wall toes, it rotates about a fixed point on the wall. The proposed pendulum UPSW concept harnesses geometric system kinematics in a novel and synergistic manner as a means of achieving damage-free and self-centering systems, while providing progressive amounts of energy dissipation capacity.

This paper presents experimental and analytical results in support of characterizing the in-plane load-deformation response of uncoupled pendulum UPSWs. Experimental results are presented to substantiate findings from a computational investigation which shows that for coefficients of friction higher than 25% there is loss of contact at the interface between the wall and the footing. This suggests that an engineered material with a lower coefficient of friction will have to be used in future research in order to ensure no/minimum contact separation at the footing interface. Although separation at the footing interface was observed, the system was able of reducing stress concentrations at the wall toes because the contact region was spread of a larger region, and due to the geometry of the interface wall walking was eliminated.

Keywords: Earthquake Engineering, Energy Dissipation, Unbonded Post-Tensioned, Shear Walls, Damage Free

1. Introduction

The core idea of using a footing interface with a circular profile in the construction of un-bonded post-tensioned shear walls (UPSWs) is to increase its energy dissipation capacity through friction. Energy dissipation is typically associated with nonlinear geometric and material behavior or devices that "release" accumulated energy through the work created, or energy used [20][25][26]. Sources dissipating work are commonly material damage, e.g., plasticity, friction, and viscous flow [13]. These mechanisms are well understood and lead to effective energy dissipation devices. A drawback is that they are not self-restoring, which can result in permanent deformations or depend on loading/unloading rate [5][6]. Due to system kinematics it can be shown that a circular profile will also provide higher relative displacements between coupled wall systems, thereby also increasing the system's energy dissipation capacity in coupled walls shear connectors. This new system is designated as a pendulum UPSW system because, instead of rocking about the wall toes, it rotates about a fixed point on the wall. The proposed pendulum UPSW concept harnesses geometric system kinematics in a novel and synergistic manner as a means of achieving damage-free and self-centering systems, while providing progressive amounts of energy dissipation. This paper focus mainly on the in-plane load-deformation response of uncoupled pendulum UPSWs.

This philosophy of system kinematics coupled with higher levels of energy dissipation capacity is verified in this research program. This objective is achieved thru two unique and complementary features, namely: (1) individual walls gliding along a circular path with no separation at the footing interface, and (2) continuous energy dissipation via devices with controllable elastic instabilities along vertical wall joints [15]. This concept is designated as a pendulum UPSW system as it rotates about a fixed point on the wall. Research is divided in three task according to the following work plan: (1) characterize the in-plane response of pendulum UPSWs as viable lateral load resisting elements, (2) develop and characterize the use of elastic meta-materials and meta-structures for dissipating energy via elastic instabilities, and (3) to characterize the response of pendulum UPSWs coupled with elastic multistable structures as connectors. At this stage of research task one has been initiated and this paper presents experimental and numerical results.

ACI 318-14 [2] specifies that unbonded post-tensioned shear walls (UPSWs) can be considered in regions of high seismic intensity provided they meet the experimental requirements of ACI ITG-5.1 [3] and the design requirements of ACI ITG-5.2 [4]. In either standard, the wall/footing interface considers only a flat surface and the main form of wall behavior is characterized by significant separation at the foundation interface. Conversely, the system under current investigation represents a departure from commonly used UPSWs, because the base is formed in the shape of an arched surface and wall behavior is best characterized as an inverted pendulum without significant separation at the foundation interface. Although rocking and pendulum concepts are used interchangeable in the literature [14], in this context, the kinematics of rocking and pendulum UPSWs are significantly different. This is described in further detail in this paper.

This paper presents preliminary results in support of the implementation of pendulum UPSW systems in the built infrastructure. Research is divided in three major tasks; however, this paper presents results regarding the in-plane response of pendulum UPSWs as viable lateral load resisting elements. At this stage, a wood-frame shear wall was tested and in the near future the scope of research will involve testing this UPSW wall under increasing levels of prestressing force, using an interface material with different friction coefficients and testing four reinforced concrete UPSW walls. Experimental results are presented to substantiate findings from a computational investigation which shows that for coefficients of friction higher than 25% there is loss of contact at the interface between the wall and the footing. This suggests that further research will need to address the use of an interface material with a lower coefficient of friction in order to ensure no or minimum contact separation at the footing interface. Preliminary results shows that the system was capable of reducing stress concentrations at the wall toes because the contact region was spread of a larger region, and due to the geometry of the interface wall walking was eliminated. Experimental results are presented to substantiate these findings.

2. Background

Reinforced concrete shear walls (RCSW) main form of energy dissipation is in the form of structural damage, which may not fit within the grand challenge of "achieving immediate occupancy and minimum economic losses following an extreme seismic event". Damage in RCSW can be categorized by extensive regions of concrete spalling and yielding of the longitudinal reinforcement. This signifies major damage with extensive repairs required after a seismic event [13]. This was the case of many RCSWs response under the 2010 Chile Earthquake [9]. Whence, the cost and consequences of this level of damage can be devastating and significantly affect local economies.

Conversely, in self-centering UPSWs the nonlinear response arises mainly from a decrease in structural stiffness during opening of gaps in connections and the elastic restrain from the posttensioning tendon. Although this form of nonlinear response results in low structural damage and the system returns to a mostly damage-free configuration after an event [20][21], it offers only minor energy dissipation [8][11]. Consequently, this response results in greater lateral displacements and higher number of displacement peaks than RCSW [17][18][27]. As a means for enhancing the life-safety and toughness of UPSWs in regions of high seismic intensity, performance, or categories, ACI ITG-5 [3][4] provides guidelines for the inclusion of energy dissipation devices. Diverse types of connectors have been proposed and studied to provide the needed energy dissipation between precast concrete walls through friction, yielding, or viscous fluids [11][24]. Different devices are described in the literature that can be used to enhance the energy dissipation of these systems and for brevity only a few are listed: (1) ductile connectors crossing vertical joints [26][20], (2) reinforcing steel bars crossing joints at the footing horizontal interface [21], (3) externally mounted fluid-viscous dampers [16][19]. Of these, yielding connectors using a flexural mechanism have been identified as the most suitable since they provide a stable hysteretic response, large displacement capacity and a large amount of energy dissipation. However, yielding connectors have important performance limitations such as: 1) their energy dissipation capacity is significant only after large inelastic deformations, 2) plastic deformations can be difficult to restore, and 3) they are not ideal for low-level, or frequent lateral demands.

Research by Belleri et al. [5] reported on the findings of testing a three-story, oblong, precast concrete building built at half-scale and tested under the Network for Earthquake Engineering Simulation (NEES). In these tests the main form of energy dissipation was by either providing vertical reinforcement across horizontal connections, or U-shaped connector in the vertical connections between two coupled walls. The building was designed using a performance-based seismic design methodology and included high performance, post-tensioned lateral force-resisting systems. Moment frames consisted of precast prestressed beam and column elements, whereas structural walls utilized unbonded post-tensioned and mild steel to provide re-centering and energy dissipation.

2.1 Critical Issues of UPSWs

Self-centering is excellent in seismic applications because, immediately after the event, the structure is functional with the added benefit of reducing financial losses due to structural and nonstructural damage and low repair costs [7]. Because of these intrinsic benefits, UPSWs are nowadays recognized systems in seismic design [3][10][26]. However, previous research demonstrates that under an MCE event UPSWs may not always behave as intended: damage-free and self-centering [5]. As such, despite the excellent performance of these rocking systems, system kinematics continues to impose high stress demands in the materials used in the construction of UPSWs. Research results from these projects and many other research programs highlight that advancing the technology of rocking UPSWs requires addressing the following critical issues.

2.1.1 Concrete crushing

Rocking mechanisms induce large concrete compressive strains at wall toes that lead to concrete crushing or concentrated damage at the wall toes. To prevent significant losses in the posttensioning forces, tendons are placed away from these high-compression regions. In addition, significant amounts of transverse reinforcement are required at the wall toes, thereby increasing construction costs [16][26].

2.1.2 Yielding of tendons

Reduction in permanent tendon forces due to steel yielding and reversed cyclic loading is critical in preserving the integrity of UPSWs. This is an issue because the posttensioning force ensures friction transfer across the foundation interface and between horizontal joints of precast panels [16][26]. As such, drift limits are stipulated to ensure that under a design event the tendons are below the yielding.

2.1.3 Wall walking

A critical advantage of UPSWs is their self-centering characteristics, which are directly attributed to the presence of the post-tensioning force. Any losses in tendon forces leads to a reduction in the contact frictional forces thereby induce wall walking [12].

2.1.5 Drift limits

To preserve the self-centering capabilities of UPSWs, ACI ITG-5.2 [4] stipulates drift limits to constrain strain demands in the concrete, tendons and yielding connectors. This is likely to restrict the use of UPSWs in many design applications, e.g., UPSWs with low axial load or aspect ratios. Combination of these issues requires setting drift limits to preserve the self-centering capabilities of UPSWs. Building on the assets of UPSWs, this paper aims at presenting results from a research program that highlights a few features of a new concept for UPSWs that can improve or eliminate technical issues that are prevalent in UPSWs.

3. Research Program

As previously stated, the research program progresses according to the following three tasks: (1) characterize the in-plane response of pendulum UPSWs, (2) develop and characterize the use of elastic meta-materials and meta-structures for dissipating energy via elastic instabilities, and (3) to characterize the response of pendulum UPSWs coupled with elastic multistable structures as connectors. As previously stated, a wood-frame shear wall was tested and in the near future the scope of research will involve testing this UPSW wall under increasing levels of prestressing force, using an interface material with different friction coefficients and testing four reinforced concrete UPSW walls

2.1 Test Setup

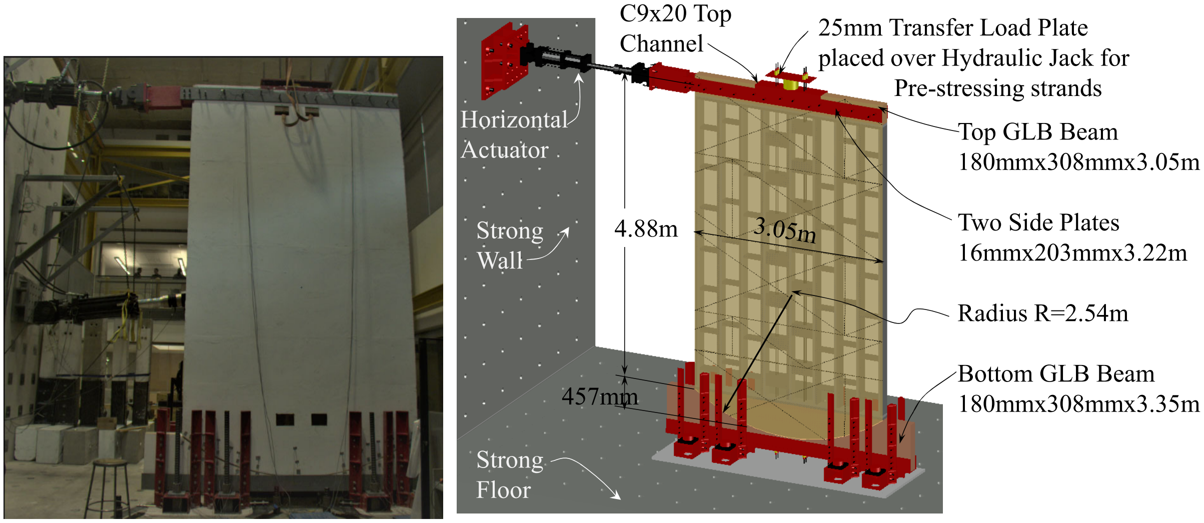
The experimental program is being conducted at the George Washington University (GWU), according to the test setup presented in Fig. 1. The unit is subjected to a series of reversed quasi-static displacement-controlled cycles to predetermined drift angles as specified in the minimum experimental requirements of ACI ITG-5.1 [3]. The wall height, width and thickness are respectively, 4.88, 3.05 and 203mm. This set of dimensions leads in a wall height to width (H/W) aspect ratio of 1.6 and a width to thickness slenderness ratio of 15. Based on this slenderness ratio the wall can be classified as a slender structure.

2.2 Construction of the X-Braced Shear Wall

As shown in Fig. 2a, the X-Brace shear wall was achieved by providing two diagonal 20-gauge galvanized steel braces on either side of the wall as shown Fig. 2. Construction of the shear walls and profiles for the glulam beam are further exemplified in Fig. 3. Vertically double 2x8 studs at 300mm were connected to the top and bottom glulam beams with double rows of 8d nails at a spacing of 100mm. Likewise, 2x8 blocking were also installed in a manner to increase the wall shear capacity. Finally, 19mm thick plywood panels were placed on both sides according to the pattern depicted in Fig. 2b. The plywood nailing diagram consisted of 10d nails at a spacing of 100mm in all blocked edges. This nailing diagram and plywood configuration will ensure a unit shear wall capacity of nearly 51kN/m far exceeding the required unit shear demand of 23kN/m.

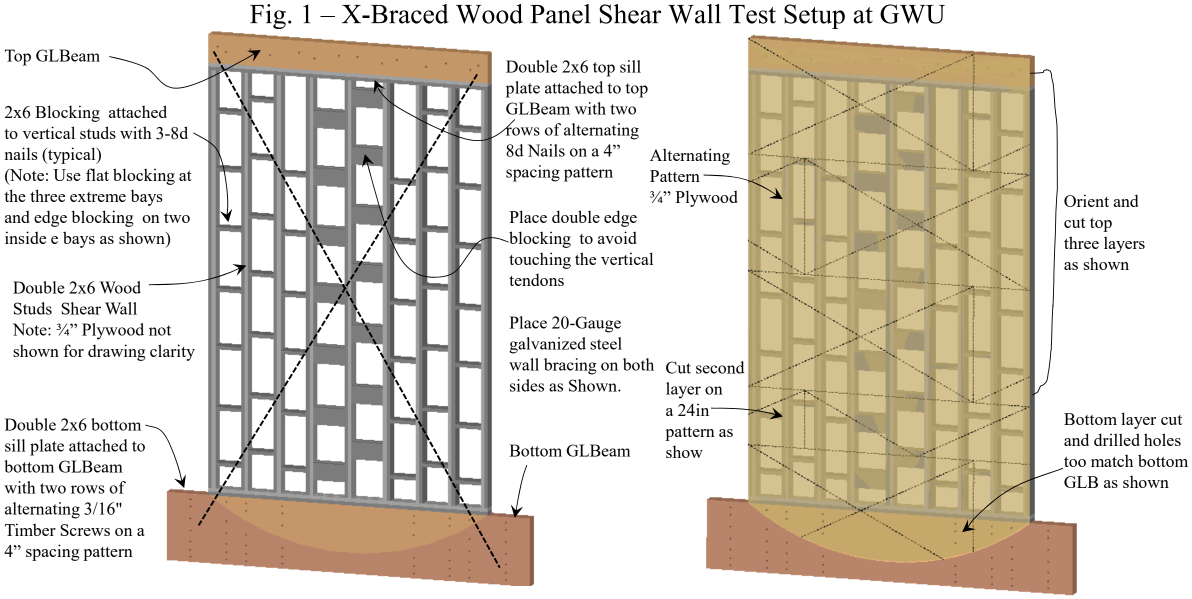
2.3 Shear Wall Attachements

As shown in Fig. 1 vertical outriggers were provided at the base of the footing as a means for controlling any potential out of plane deformation of the test unit. Assembly of the test unit is described in Fig. 4.



(a) Laboratory Test Setup at GWU (b) Plywood Sheathing Layout

Fig. 1 – X-Braced Wood Panel Shear Wall Test Setup at GWU



(a) Vertical Studs Layout (b) Plywood Sheathing Layout

Fig. 2 – X-Braced Wood Panel Shear Wall Sheathed with Wood Structural Panels

4. Numerical Modeling and Results

The main objective of the finite element model (FEM) simulations was to numerically characterize the in-plane response of the test unit depicted in Fig. 1. Simulations involved 2D and 3D simulations which consisted of investigating the influence that wall aspect ratio, base radius, base friction, number and position of tendons, and initial posttensioning stress have on the response of pendulum UPSWs under lateral loads. ABAQUS 6.14-2 [1] was chosen as the software platform because of its ability to model the initial posttensioning forces, and as importantly its advanced algorithms for modelling contact surfaces at the footing interface. Fig. 5 shows the FEM simulations that were used in charactering the optimum circular profile at the footing interface for UPSWs. In lieu of the work presented in this paper and for the wall geometry presented in Fig. 1 with a height of H=4.88m and width of W=3.05m, the optimum radius was

R=2.54m, which represents a wall/radius of 1.20. However and for brevity, only numerical results for the optimum design wall are reported and discussed in the next sections of this paper.

(a) (b) (c)

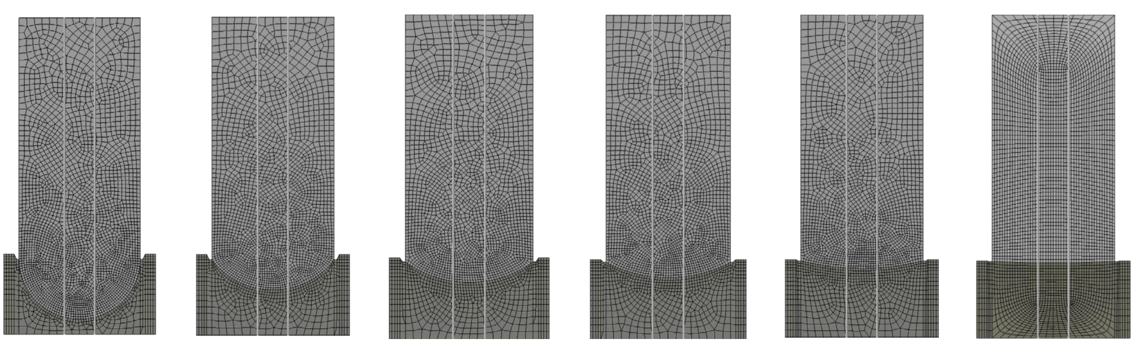
(a) Construction of 2x8 Double Wood Studs Wall
(b) Profile and cuts for Top and Bottom Glulam Beams
(c) Installation of Bottom Glulam Beam on Lower Support

Fig. 3 – Wall Construction and Installation of Top and Bottom Glulam Beams

(a) (b) (c)

(a) Installation of Bottom Support to Strong Floor
(b) Complete Top part of X-Braced Shear Wall
(c) Final Construction phase of X-Braced Shear Wall

Fig. 4 – Construction Phase for the X-Braced Wood Panel Shear Wall Test Setup



a) *W/R*=2.0 b) *W/R*=1.5 c) *W/R*=1.2 d) *W/R*=1.0 e) *W/R*=0.5 f) *W/R*=0 (Flat)

Fig. 5: Uncoupled UPSWs Geometry for Conducting FE Simulations

4.1 3D-Finite Element Model

In order to numerically characterize the in-plane response of uncoupled UPSWs high-fidelity modeling was conducted using the three-dimensional model depicted in Fig. 6 using the program ABAQUS [1]. In this model, the wall and footing were simulated with *C3D8R* 8 node brick elements. The wall was discretized with a denser mesh than the footing, with the wall and footing element sizes of 2 and 4, respectively. This was important for achieving best results for the interface between these two regions. Accordingly, the wall and footing were set as the slave and master surface, respectively. According to ABAQUS [1] user's manual, it is best to define the coarser mesh as the master surface and the denser mesh as the slave surface. This modelling condition is effective in preventing penetration between these two surfaces.

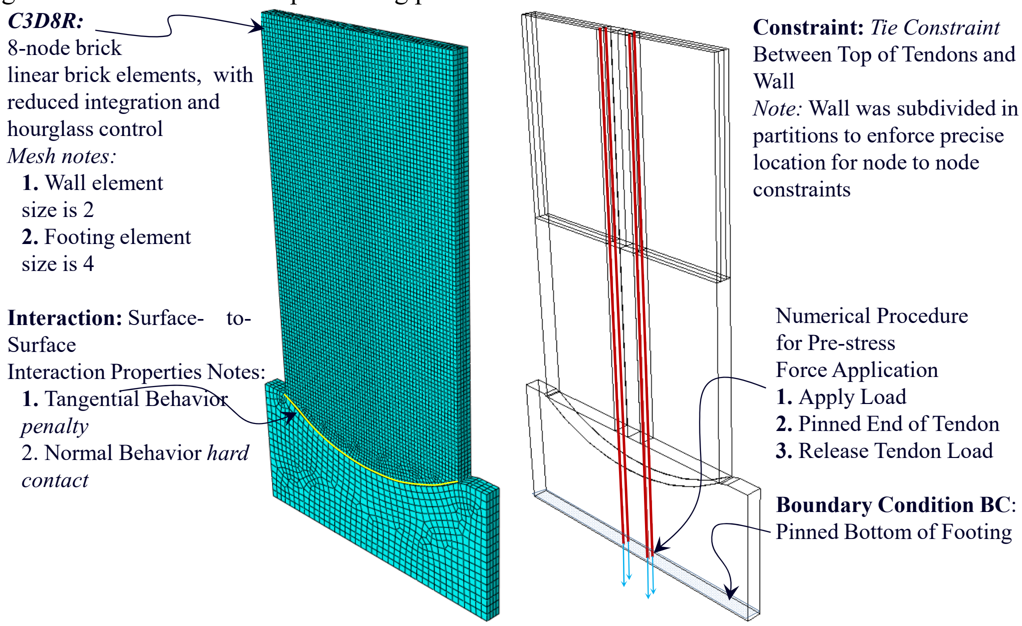
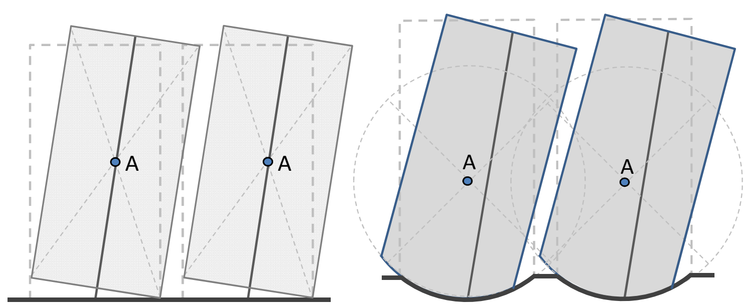


Fig. 6 – 3D Finite Element Model used in investigating the X-Braced Shear Wall Test Setup

4.1 Numerical Results

4.1.1 Influence of Friction at the Footing Interface on the Global Load Deformation Response

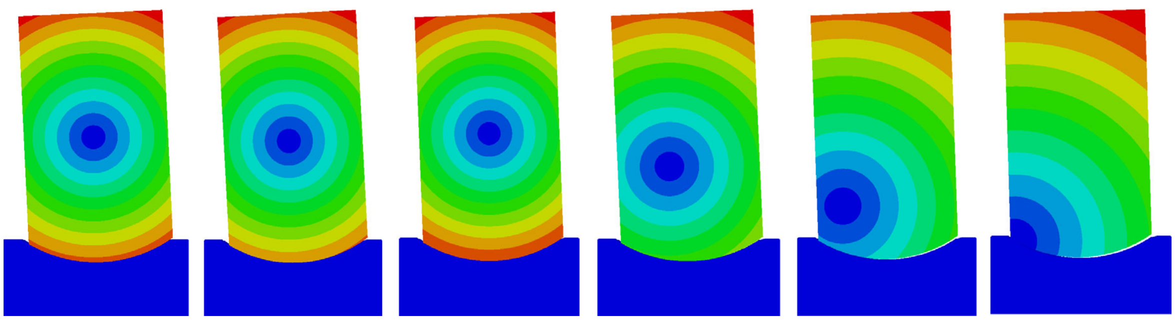
As previously stated, ACI 318-14 [2] allows UPSWs in high seismic regions provided they meet the experimental requirements of ACI ITG-5.1 [3] and the design requirements of ACI ITG-5.2 [4]. In either standard, the main form of wall behavior is characterized by rocking with significant separation at the foundation interface. Although in rocking walls, which are described herein as a wall with a flat surface at the footing interface, the system response will always be characterized by rocking with significant separation at the footing interface. The global response of the unit investigated in this paper, is schematically depicted in Fig. 7b, and represents a significant departure from rocking UPSWs. In this instance, the base is formed in the shape of an arched surface and wall behavior is best characterized as an inverted pendulum.



(a) Rocking UPSWs (b) Pendulum UPSWs

Fig. 7 – UPSW Systems Kinematics

Although the arched surface is likely to result in minimum to no separation at the foundation interface, experimental investigation as shown that the friction coefficient at the wall interface coupled with the pre-stressing forces may in fact result in some level uplift of UPSWs. As such further research is currently under investigation to further substantiate this finding. Fig. 8 clearly corroborates this finding. In Fig. 8a to Fig. 8c it is clearly that at the maximum drift level the center of rotation is near the center of the interface radius. As the coefficient of friction increases, as shown in Fig. 8d to Fig. 8e, the center of rotation migrates towards the corner of the wall and it is obvious the wall experiences uplift. The coefficient of friction for the glulam beams used in the construction of the interface was evaluated at 27%. Since for coefficients of friction higher than 25% there is loss of contact at the interface between the wall and the footing, this suggests that an engineered material with a lower coefficient of friction will have to be used in future research. This is necessary in order to ensure no/minimum contact separation at the footing interface. Conversely, higher prestressing forces will result in contact separation for coefficient of friction higher than 30%. As such, current research is underway, for quantifying the relation between prestressing force and coefficient of friction necessary to ensure no loss of separation at the interface of UPSWs to the footing interface.



(a) μ=10% (b) μ=15% (c) μ=20% (d) μ=25% (e) μ=27% (f) μ=30%

Fig. 8 – Friction Influence on the Global Deformation of UPSWs under Lateral Loads to Peak Drift of 3%

4.1.1 Load Deformation Response of the Test Unit

Load versus top deformation and for different level of friction are presented in Fig. 9. As before, this figure clearly exemplifies that as the coefficient of friction increases, as shown in Fig. 9d to Fig. 9e, the pronounced effects of rocking are further intensified. It is also clear that as the coefficient reduces there is a coupled reduction in the lateral resistance of the test unit. Referring to Fig. 9c, Fig. 9d Fig. 9f, it is clear that while the lateral resistance reduces by approximately 45%, their energy dissipation capacity is orders of magnitude higher. However, it must also be considered that when the energy dissipation capacity of the system increases, there is also a significant reduction in the lateral displacement demands on the system. This condition will be evaluated in future research using ground motions and the shake table at GWU [22][23][25].

5. Experimental Program

The experimental program is being conducted at the George Washington University (GWU), according to the test setup presented in Fig. 1. The unit was subjected to a series of displacement-controlled reversed quasi-static cycles to predetermined drift angles. The target drift angles were as specified in the minimum experimental requirements of ACI ITG-5.1 [3].

5.1 Load-Deformation Response

The experimental and analytical load-deformation response for the test unit is depicted in Fig. 10. This figure clearly shows that the shear capacity of the test unit was nearly constant under reversed cyclic loading to the same drift levels. For instance, at the 3% drift level the registered loads in kN were, respectively, 118, -139, 107, -112, 117, -112. The shape of the experimental results also indicate gap opening at low drift levels but increasing stiffness with moderate levels of energy dissipation capacity. The unit also displayed no signs of damage. In future research this unit will be subjected to increasing levels of prestressing forces and interface material with lower coefficient of friction. The plots corresponding to the "*Abaqus 3D Analysis*" were for the 27% coefficient of friction and results shows the analytical registered load-deformation response approximates reasonably well the lateral load response of the test unit.

5.2 System Performance Evaluation

Response at the peak drift level of 3% is presented in Fig. 11. This figure clearly shows loss of contact at the interface and uplifting at the wall base, however, nearly a quarter of the interface length remained closed.

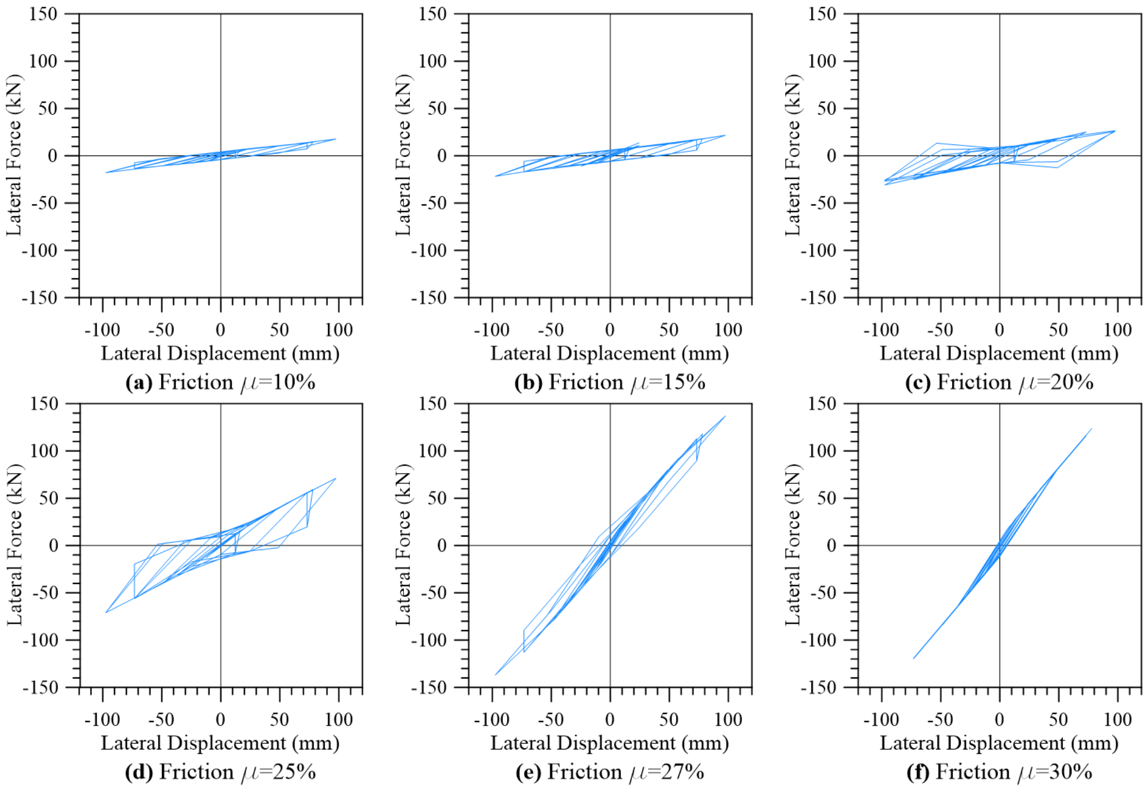


Fig. 9 – Load Deformation for Different Values of Coefficient of Friction at Circular Interface

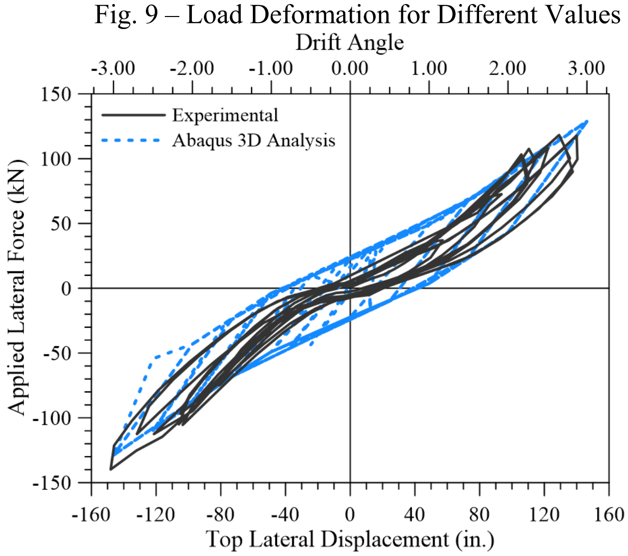


Fig. 10 – In-Plane Load Deformation Response

Fig. 11 – System Performance Evaluation 3% Drift

6. Acknowledgements

The research presented in this paper is part of a collaborative research project supported by the U.S. National Science Foundation under grant numbers CMMI-1762170 (PI: P.F. Silva) and CMMI-1762119 (PI: R. Burgueño). Special thanks to Owen Scholl (High Bay Manager), The GW Machine Shop, and the undergraduate students, Pengyu Chen, Zachary Stecher, Mohammad Badeeb, Florencia Dayan, and Savana Stewart are indeed appreciated.

7. Conclusions

Experimental results substantiate findings from a computational investigation which shows that for coefficients of friction higher than 25% there is loss of contact at the interface between the wall and the footing. This suggests that an engineered material with a lower coefficient of friction will have to be used in future research in order to ensure no/minimum contact separation at the footing interface.

Research results clearly exemplifies that as the coefficient of friction increases, pronounced effects of rocking are intensified in the units investigated in this research. It is also clear that as the coefficient of friction reduces there is a coupled reduction in the lateral resistance of the test unit. Conversely it is also impactful, that while the lateral resistance reduces by approximately 45%, their energy dissipation capacity is orders of magnitude higher. Previous research as shown that when the energy dissipation capacity of system increases, there is also a significant reduction in the lateral displacement demands on the system. As such, it can hypothesized that the superior energy dissipation capacity of pendulum UPSW translates to an improved system performance. This condition will be evaluated in future research using nonlinear time history analysis for systems subjected to ground motions.

8. References

[1] Abaqus (2014). "User Manual Version 6.14-2: Dassault systems", Simulia Corp. USA.

[2] ACI (2014). "ACI 318-14: Building Code Requirements for Structural Concrete and Commentary," *American Concrete Institute*, Farmington Hills, MI, 520 pp.

[3] ACI Innovation Task Group 5.1 (2007). "Acceptance Criteria for Special Unbonded Post-Tensioned Precast Structural Walls Based on Validation Testing and Commentary. ACI ITG-5.1. Farmington Hills, MI ACI.

[4] ACI Innovation Task Group 5.2 (2009). "Requirements for Design of a Special Unbonded Post-Tensioned Precast Shear Wall Satisfying ACI ITG-5.1 (ACI ITG-5.2-9) and Commentary. Farmington Hills, MI: ACI.

[5] Belleri, A., Schoettler, M.J., Restrepo, J.I., and Fleischman, R.B. (2014). "Dynamic Behavior of Rocking and Hybrid Cantilever Walls in a Precast Concrete Building," ACI Structural Journal, 111(3), 661-672.

[6] Bertoldi, K., and Boyce, M. (2008). "Mechanically triggered transformations of phononic band gaps in periodic elastomeric structures." *Physical Review B*, 77(5), 052105.

[7] Bora, C., Oliva, M.G., Nakaki, S.D., and Becker, R. (2007). "Development of a Precast Concrete Shear-Wall System Requiring Special Code Acceptance," PCI Journal, 51(1), 122-135.

[8] Chancellor, N. B., Eatherton, M. R., Roke, D. A., and Akbaş, T. (2014). "Self-Centering Seismic Lateral Force Resisting Systems: High Performance Structures for the City of Tomorrow, *Buildings*, 4, 520-548.

[9] EERI (2010). "Chile Earthquake Clearinghouse, The Mw 8.8 Chile Earthquake of February 27, 2010" EERI Special Earthquake Report, 20 pp. https://www.eeri.org/wp-content/uploads/Van_Turkey_eq-report.pdf and http://eqclearinghouse.org/co/20100227-chile/

[10] Englekirk, R.H. (2002). "Design-Construction of The Paramount — A 39-Story Precast Prestressed Concrete Apartment Building," PCI Journal, 47(4), 56-71.

[11] Henry, R. S., Aaleti, S., Sritharan, S., and Ingham, J. (2010). "Concept and Finite-Element Modeling of New Steel Shear Connectors for Self-Centering Wall Systems." *Journal of Engineering Mechanics*, 136(2), 220-229.

[12] Holden, T., Restrepo, J.I., Mander, J.B. (2003). "Seismic Performance of Precast Reinforced and Prestressed Concrete Walls," ASCE Journal of Structural Engineering, 129(3), 286-296.
[13] Hose, Y. D., Silva, P. F., and Seible, F. (2000). "Performance Evaluation of Concrete Bridge Components and Systems under Simulated Seismic Loads," *EERI Earthquake Spectra*, 16(2), 413-442.
[14] Housner, G.W. (1963). "The Behavior of Inverted Pendulum Structures during Earthquakes," *Bulletin of the Seismological Society of America*, 53(2), 403-417.
[15] Hu, N., and Burgueño, R. (2015). "Buckling-induced Smart Applications: Recent Advances and Trends." *Smart Materials and Structures*, 24(6), 063001.
[16] Kurama, Y. C. "2000) "Seismic Design of Unbonded Post-Tensioned Precast Concrete Walls with Supplemental Viscous Damping," ACI Structural Journal, 97(4) 641-651.
[17] Kurama, Y. C. (2002). "Hybrid Post-Tensioned Precast Concrete Walls for Use in Seismic Regions," PCI Journal, 47(5), 36-59.
[18] Kurama, Y.C., Sause, R., Pessiki, S. and Lu L.W. "2002) "Seismic Response Evaluation of Unbonded Post-Tensioned Precast Walls," ACI Structural Journal, 99(5) 648-658.
[19] Marriott, D., Pampanin, S., Bull, D., and Palermo, A. (2008). "Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems with Alternative Dissipating Solutions," *2008 Proceedings of the New Zealand Society for Earthquake Engineering Inc.*, April 2008, Wairakei, New Zealand, Paper No. 39, 16 pp, http://db.nzsee.org.nz/2008/Contents.htm
[20] Perez, F.J., Pessiki, S., and Sause, R. (2004). "Seismic design of unbonded post-tensioned precast concrete walls with vertical joint connectors," PCI journal, 49(1), 58-79.
[21] Restrepo, J.I., Rahman, A. (2007). "Seismic Performance of Self-centering Structural Walls Incorporating Energy Dissipators," ASCE Jounrla of Structural Engineering, 133(11), 1560-1570
[22] Sangtarashha, A., Silva, P.F., and Burgueño, R. (2012). "P-Delta Effects in Limit State Design of Slender RC Bridge Columns," Proceedings *15th WCEE World Conference on Earthquake Engineering,* Lisbon, Portugal, No. 4706, 10pp., http://www.nicee.org/wcee.
[23] Sangtarashha, A., Silva, P.F., and Burgueño, R. (2012). "P-Delta Mass Rig System for Shake Table Tests of Slender Reinforced Concrete Columns," *Proceedings 15th WCEE World Conference on Earthquake Engineering*, Lisbon, Portugal, No. 2503, 10 pp., http://www.nicee.org/wcee.
[24] Schultz, A. E., and Magaña, R. A. (1996). "Seismic behavior of connections in precast concrete walls." *ACI Special Publication*, 162, 273-312.
[25] Silva, P.F., Sangtarashha, A., and, Burgueño, R. (2015) "Mass Rig System for Shaking Table Tests of Slender Columns," *Earthquake Engineering & Structural Dynamics*, 44(15), 2717 – 2736.
[26] Stanton, J.F., and Nakaki, S.D. (2002). "Design Guidelines for Precast Concrete Seismic Structural Systems," PREcast Seismic Structural Systems (PRESSS) Report No. 01/03-09, University of Washington (UW) Report No. SM 02-02, Department of Civil Engineering, University of Washington, Seattle, WA, 118 pp.
[27] Toranzo, L.A.; Restrepo, J.I.; Mander, J.B.; and Carr, A.J. (2009). "Shake-Table Tests of Confined-Masonry Rocking Walls with Supplementary Hysteretic Damping," *Journal of Earthquake Engineering*, 13(6), 882-898.