INFLUENCE OF LARGE AXIAL LOADS IN ROCKING WALLS AND REINFORCED CONCRETE WALLS

Rene Francisco Nunez Orellana* **Supervisor: Dr. Susumu Kono****
MEE17716

ABSTRACT

This work introduces the concept of rocking structures with the property of self–centering, with a special focus on Rocking Walls (RWs), as damage–controlling structures, to incorporate them into the new Seismic Design Code of El Salvador. In this regard, analytical models using finite element methods based on the multiple axial spring macro model and the shear flexure interaction multi–vertical line element model (SFI–MVLEM) are developed in the software OpenSees, to predict the non–linear behavior of both RWs and Reinforced Concrete (RC) walls, in order to analytically evaluate the influence of large axial loads in terms of energy and provide design recommendations for RWs to control axial–flexural behavior and to calculate design capacities and demands. The analysis of the influence of axial load revealed that base shear increases with axial load ratio, which is more accentuated in RWs than in RC walls with the 86%. The hysteretic damping, in contrast to base shear, reduces for RC walls, while for RWs increases, this due to the inelastic energy dissipation, which depends on both strength and ductility, and is essentially the same in spite of the axial load ratio for RC walls and increases with axial load ratio in RWs, because of hysteretic behavior.

Keywords: Self–Centering, Rocking, OpenSees, Hysteretic Damping, Residual Drift.

1. INTRODUCTION

A high earthquake disaster risk potential in the world has been demonstrated in the last 20 years, which is exacerbated by the current high levels of hazard, vulnerability and exposure, as indicated by earthquake statistics of USGS, the emergency events database of CRED and the UN's world population prospects. In this regard, in the framework of the UN SDGs, developing resilient and sustainable infrastructure to make cities safe is one of the major world's commitments. In this context, on May 18th 2018, the government of El Salvador started the execution of the project "Action Plan for the Implementation of the Governability Index and Public Politics for Risk Disaster Management", which is a two–year project whose main objective is to reduce the seismic disaster risk of constructions by upgrading the national seismic design code. In this context, this work introduces the concept of damage controlling structures with the property of self–centering, with a special focus in RWs in order to take advantage of the desirable seismic characteristics related to the self–centering ability and capability of undergoing nonlinear lateral displacements with little damage, to develop resilient and sustainable cities. Since RWs are more suited to DDBD than to Force Based Design (FBD), within PBEE, as damage is more directly correlated to displacement than to forces, the DDBD is proposed as the design method for SRWs. Since in El Salvador RC walls are mostly used, in mid–rise to high–rise buildings, with bare frames as lateral force resisting systems, they are subjected to large axial loads especially in bottom floors. Given the importance of equivalent stiffness to the maximum displacement and of equivalent damping to define the equivalent SDOF in the DDBD; and considering the limited research on the influence of axial loads in terms of energy dissipation, for the implementation of RWs in the framework of PBEE, it is essential to evaluate the influence of axial loads in RWs and RC walls in terms of energy dissipation, and demonstrate the higher performance of RWs.

---

[*] Ministry of Public Works, Transportation and Housing and Urban Development (MOPTVDU), El Salvador.

[**] Professor, Department of Architecture and Building Engineering, Tokyo Institute of Technology, Japan.

2. DEFINITION AND BEHAVIOR OF ROCKING WALLS

Unbounded Post–Tensioned Precast Concrete Walls are precast concrete structural walls, which are composed by one (uncoupled walls) or more (coupled walls) vertical wall panels. Each vertical wall panel can be cast as a single element, or as several separate wall elements that are subsequently joined by rigid connections. Wall panels are connected to the foundation by continuous unbounded post–tensioned tendons, which along with gravity loads, act as a restoring force to provide the self–centering property. Supplemental energy dissipators such as mild steel reinforcing bars across the wall to foundation joint in uncoupled walls, or shear connectors along vertical joints in coupled walls can be included to increase energy dissipation. RWs referred in this study are Unbounded Post–Tensioned Precast Concrete Walls that are composed by one vertical panel cast as a single element without energy dissipators. The behavior of unbounded post–tensioned precast concrete walls is flag–shaped, as typical in prestressed concrete structures. The flag–shape behavior can be summarized in four steps, as shown in Figure 1, assuming wall–foundation interface has no flexibility and energy dissipation devices are rigid–perfectly plastic. In the absence of lateral force, a uniform stress distribution develops wall–foundation interface due to initial post–tensioning force and self–weight (restoring forces). As the lateral force is applied, the stress distribution shifts to a critical point (F_{Rock}), where the resultant force at the outermost fiber of the wall is zero (Figure 1 a)). At this state, if no energy dissipators are provided, wall uplift begins, otherwise, as lateral load continues to increase, energy dissipators activate, and take the load and forces in them until yield (Figure 1 b)). If energy dissipators are perfectly rigid before yielding, the gap will not open until yielding of devices occurs. After yielding of energy dissipators the gap opens, and the system initiates the non–linear stiffness range, which is essentially controlled by elongation of post–tensioning tendons (Figure 1 c)). When the lateral load is removed, the structural wall returns to the original position by the restoring forces without any structural damage or residual deformation (Figure 1 d)). The same behavior occurs when the wall is loaded in the opposite direction. The structural limits states in the Performance Based Seismic Design (PBSD) are defined from the behavior RWs.

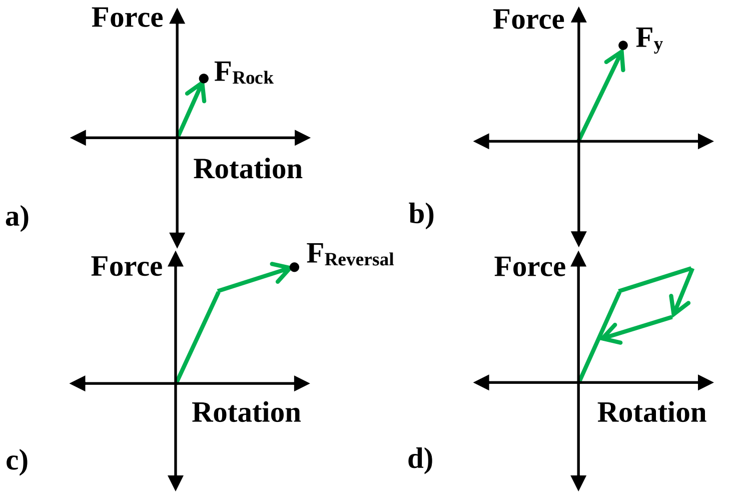


Figure 1. Behavior of Rocking Walls.

3. ANALYTICAL MODELS FOR ROCKING WALLS AND RC WALLS

3.1. Analytical Modeling of Rocking Walls

The multiple axial spring macro model was developed in OpenSees to simulate the cyclic behavior of RWs, as shown in Figure 2. Since RWs concentrate the inelastic demand at the wall to foundation interface, the behavior of wall panel is expected to be essentially elastic; therefore, the wall panel is modeled as an elastic beam–column element. The critical interface, where inelastic demand is concentrated through a gap opening and closing, is modeled using an array of uniaxial (compression only) nonlinear contact springs (zeroLength elements), distributed in X– direction, whose force–deformation nonlinear behavior is defined from the modified Kent–Park stress–strain model, considering the influence area of each spring and the effective length according to the recommendations of Perez et al. (2007). The post–tensioning (PT) tendons and the corresponding initial prestressing force are modeled using corotational truss elements and uniaxial initial strain materials respectively, and the

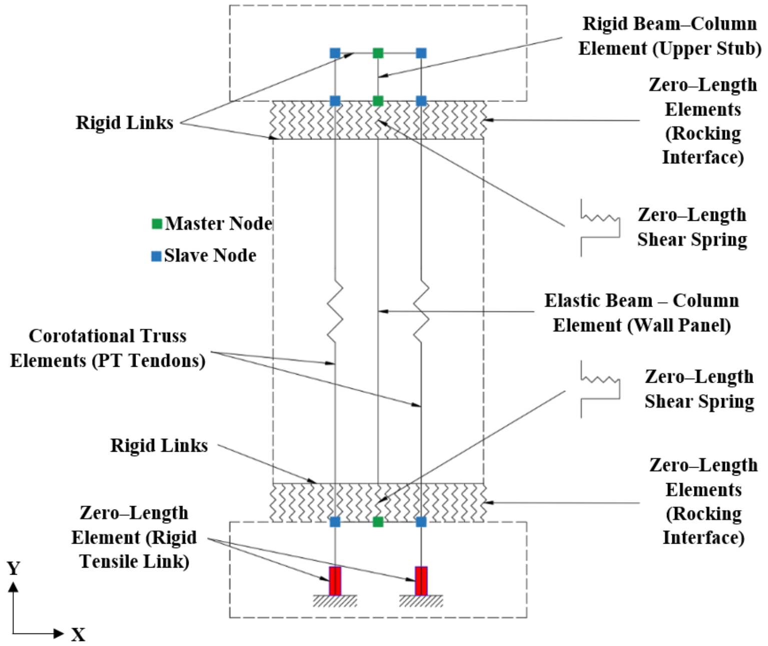


Figure 2. Multi Axial Spring Macro Model.

nonlinear stress–strain behavior defined by the Menegotto–Pinto model. In order to create a double rocking interface to reproduce the test behavior, boundary conditions and elements connectivity are critical. In this regard, at the base of the wall, springs are fully constrained at the bottom end to the floor, while are rigidly connected to the initial node of the wall panel at the top end by rigid links. The springs at the top interface, to model the double rocking, are rigidly connected to the final node of the wall panel, while at the top, translational and rotational DOFs of the springs are constrained to be those of the rigid beam element which simulates the stub. Since there is no restoring force to control and reverse the shear slip displacements that may occur due to lateral loads, shear slip along the wall to foundation joint is to be avoided, therefore shear springs with large stiffness are provided by using a zeroLength element modeled in the middle of the rocking interface. The unbounded behavior of PT tendons is modeled by kinematically constraining lateral and rotational DOFs to the corresponding element nodes of the wall at each rocking level, also, in order to simulate the anchorage of PT tendons to the rigid upper stub, translational and rotational DOFs are constrained with that of the top node of the rigid beam element. The accuracy of the 2D multiple axial spring macro model is verified against the experimental results of the specimen NSW6A tested in TIT, as shown in Figure 3. The results show a good accuracy of prediction for initial stiffness and base shear in both, positive and negative sides for global behavior, which error is below 2%. The accuracy of the model to predict the local behavior is investigated with the behavior of PT force, the predictions showed a good agreement with experimental results, and since the analytical model considers losses due to elongation effects only and does not consider losses due to friction and anchorage wedge seating, it can be demonstrated that elongation of PT tendons dominate the PT force variation.

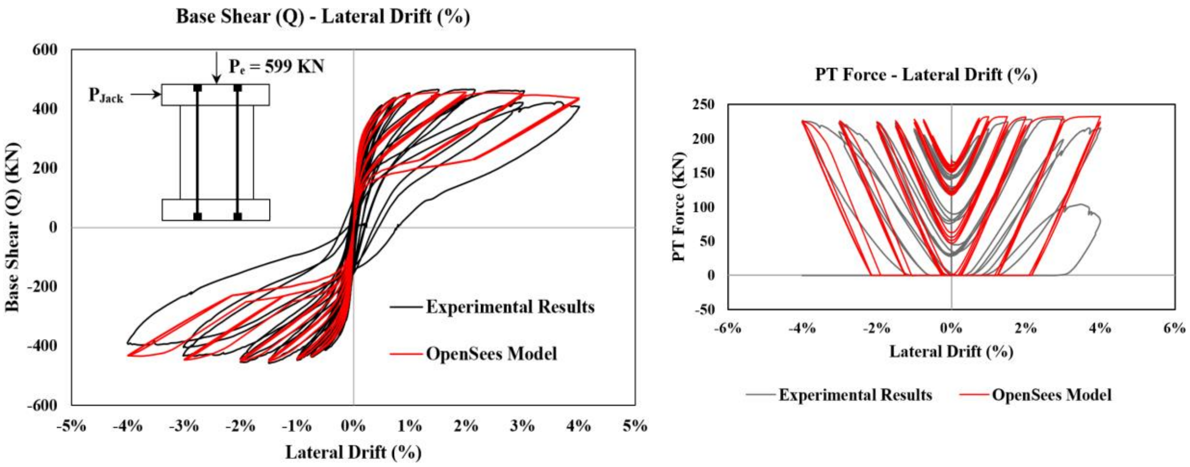


Figure 3. Comparison of Analytical and Experimental Results.

3.2. Analytical Modeling of RC Walls

The Shear Flexure Interaction Multi Vertical Line Element Model (SFI–MVLEM, Kolozvari et al., 2015), which is a finite element modeling approach that captures the experimentally observed shear flexure interaction, was developed in OpenSees to simulate the cyclic behavior of RC walls. The wall was modeled as a stack of five SFI–MVLEM elements placed upon one another, containing five reinforced concrete panels each, as shown in Figure 4. The reinforced concrete panels represent a two–dimensional constitutive model relationship that relates the strain field imposed on each of them ($\varepsilon_x, \varepsilon_y$ and γ_{xy}) to the resulting stress field on concrete (σ_x, σ_y and τ_{xy}). Thereby, the coupling of axial and shear responses is achieved at a panel level, which further incorporates interaction between flexural/axial and shear forces and deformations at the model level (Kolozvari et al., 2015). The flexural response of the model element is captured through the axial deformation of the reinforced concrete panels in the vertical direction (Y-), and the relative rotation between top and bottom faces (curvature) of the wall element, as well as the shear deformations are concentrated at the center of rotation in the central axis of the element. Thus making the coupling of axial/flexural and shear to occur at a panel level. The accuracy of the SFI–MVLEM is verified against the experimental results of the specimen NSW6 tested in TIT, as shown in Figure 5. The results show a good accuracy of prediction for initial stiffness and base shear in both, positive and negative sides for global behavior, which error is below 1.5%. The accuracy of the model to predict the local behavior is investigated with the crack pattern, since it is essentially controlled by strain field at a panel level, and is representative of the failure mode and the interaction between shear and axial/flexure behavior. The results show that the model reproduces the cracking pattern with a good agreement in the orientation of cracks, which means that SFI–MVLEM is capable of predicting the failure mode with reasonable accuracy and can capture the shear flexure interaction experimentally observed.

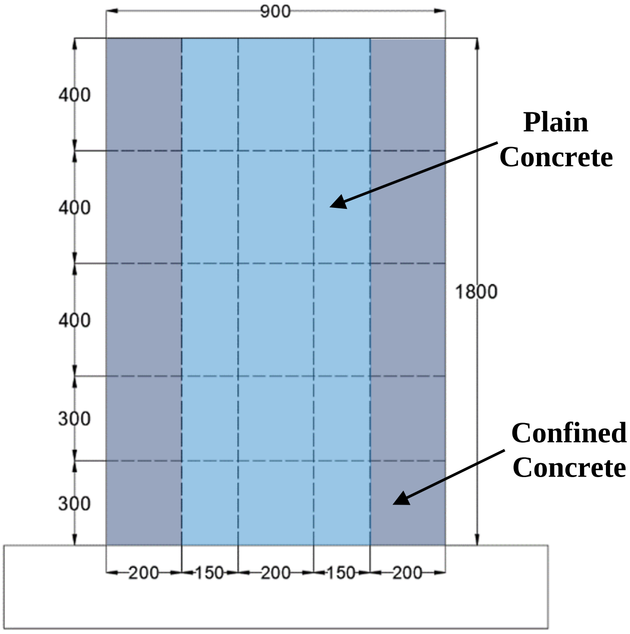


Figure 4. Shear Flexure Interaction Multi Vertical Line Element Model.

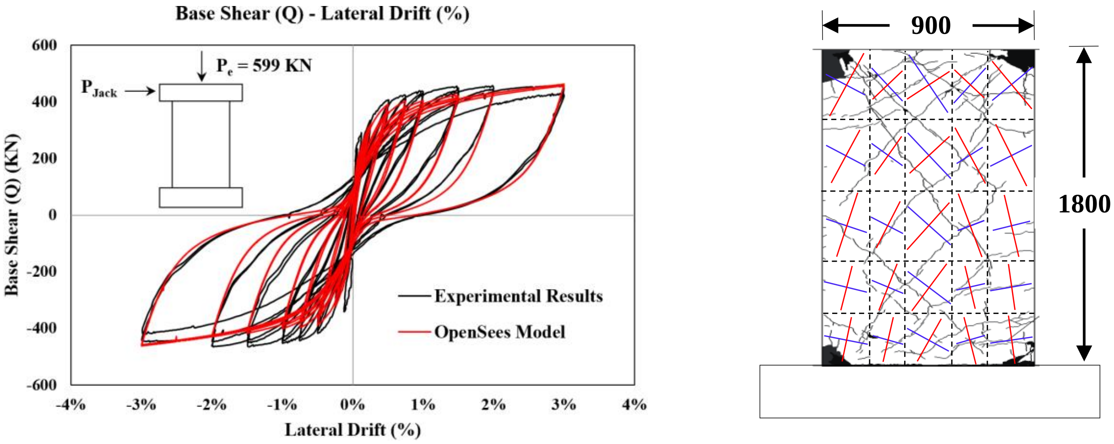


Figure 5. Comparison of Analytical Predictions wit Experimental Results.

4. INFLUENCE OF AXIAL LOADS IN RWs AND RC WALLS

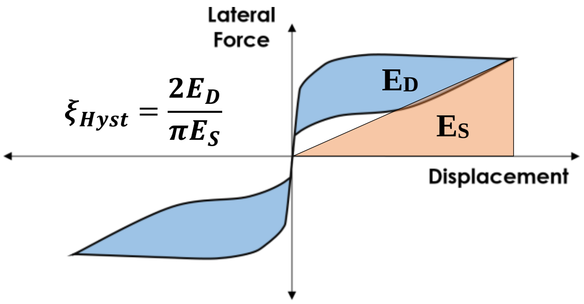
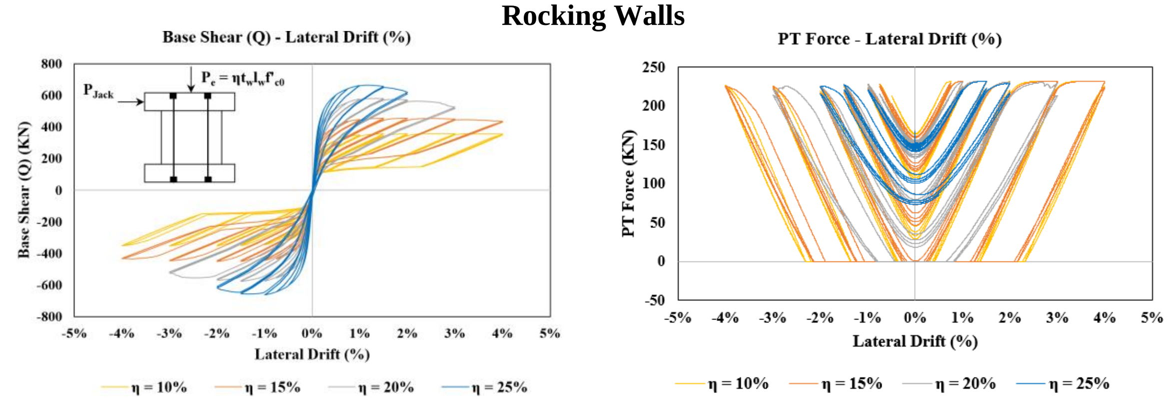


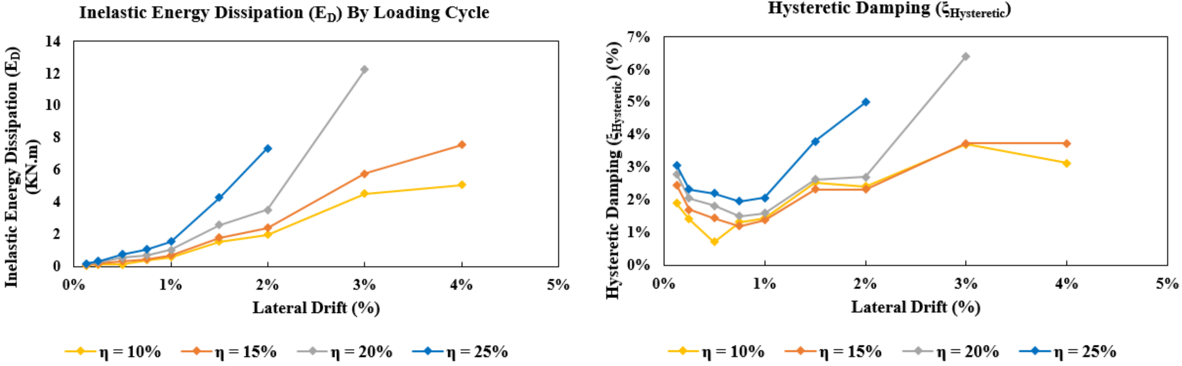
Figure 6. Equivalent Viscous Damping According to Jacobsen's Theory.

The hysteretic damping is evaluated according to the approach introduced by Jacobsen (1930) (Figure 6). The analysis shows that as axial load ratio increases, inelastic energy dissipation (E_D) and hysteretic damping (ξ_{Hyst}) increase in RWs, while in RC walls E_D remains essentially the same in spite of the axial load ratio and consequently ξ_{Hyst} reduces. This is due to the cyclic behavior of RC walls, as axial load increases, the behavior resembles a flag shape hysteretic behavior, since residual deformation reduces.

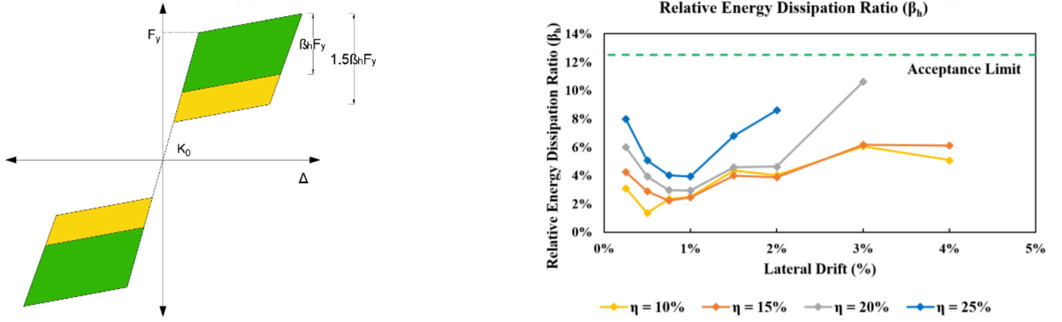
Rocking Walls



a) Base Shear (Q)–Lateral Drift (%). b) PT Force – Lateral Drift (%).



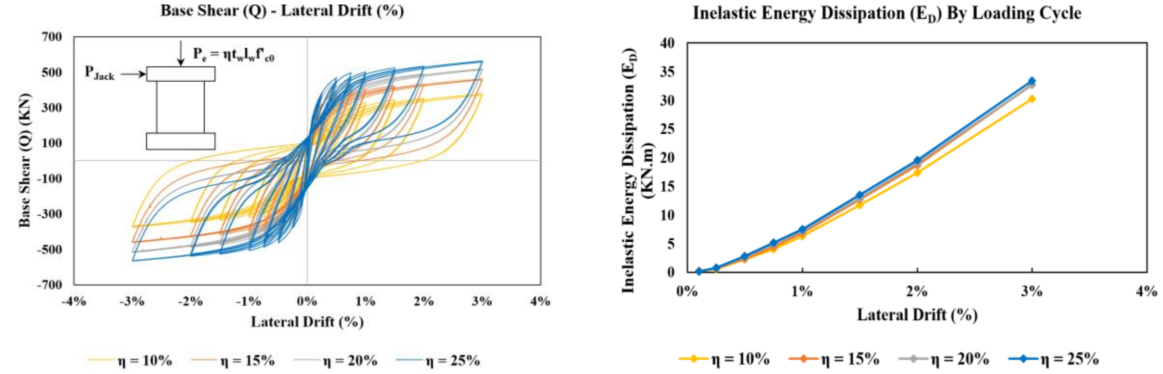
c) Inelastic Energy Dissipation. d) Hysteretic Damping.



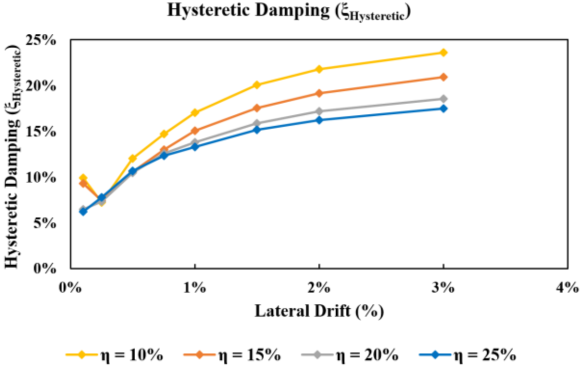
e) Definition of Relative Energy Dissipation Ratio. f) Influence of Relative Energy Dissipation Ratio.

Figure 7. Influence of Axial Load in Rocking Walls.

Reinforced Concrete Walls



a) Base Shear (Q)–Lateral Drift (%). b) Inelastic Energy Dissipation.



c) Hysteretic Damping.

Figure 8. Influence of Axial Load in RC Walls.

The results show the dependence of E_D on strength, ductility and residual deformation, which are the parameters defining the area within the hysteresis loop. In both RWs and RC walls base shear increases with axial load ratio, but the increase is more accentuated in RWs with the 86% than in RC walls, however, ductility reduces in RWs. RC walls have shown greater ξ_{Hyst} than RWs, but because of the residual deformation, which are a major indicator of damage, RWs as damage controlling structures, which have negligible residual deformation, and consequently less damage, are deemed as superior seismic performance structures.

5. CONCLUSIONS

- The base shear for RC walls, such as for RWs, increases with axial load ratios below the balance point of the interaction curve, however, the influence of axial load ratio in the base shear is more accentuated in RWs with an increase of 86% than in RC walls with an increase of 37%. Also, regarding post–tensioning force in tendons of RWs, it was found not to be affected by axial load ratio, but instead by the gap opening, therefore failure of the RWs is controlled by concrete crushing at compression toe.
- The E_D increases with axial load ratio for the same level of lateral drift in RWs, while for RC walls reduces for axial load ratios below the balance point of the interaction curve, due to the hysteretic behavior influenced by the reduction of residual drift. On the other hand, the relative energy dissipation ratio (β_h) (Figure 7 f)) according to ACI ITG–5.1–07 acceptance criteria, indicates that to have satisfactory seismic performance in terms of energy dissipation, β_h should be greater than 12.5%, therefore, additional energy dissipation devices should be provided.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Susumu KONO and Dr. Tatsuya AZUHATA for their continuous support, valuable suggestion and instruction during my study.

REFERENCES

Kolozvari, K., Orakal, K., Wallace, J., 2015, PEER, Berkeley, California
Perez, F.J., Sause, R., Pessiki, S., 2007, Journal of Structural Engineering (ASCE).
Zhang, C., 2015, McMaster University, Ontario, Canada.