Casa Adelante: Behavior, Design, Modeling Choices, and Performance Insights of a Rocking Mat Foundation System

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Abstract

Casa Adelante is a new nine-story building located in San Francisco's Mission District. The building provides 93 affordable housing units to low income seniors, with 20% of the units reserved for formerly homeless seniors. The reinforced concrete structure is comprised of post-tensioned slabs, gravity columns, reinforced concrete shear walls, and mat foundation. Because the economically vulnerable population has limited alternatives for shelter after a major earthquake, special efforts were directed towards developing a resilient and high-performance building without adding significant construction costs. The building was designed to have a rocking mat foundation and analyzed using non-linear response-history procedures per the PEER Tall Buildings Initiative guidelines and capacity-based design principles. Lead extrusion dampers developed by Prof. Geoffrey Rodgers at the University of Canterbury in New Zealand were placed in the mat slab at critical locations. Damage and loss estimates were developed for the rocking mat design and compared to those of a conventional shear wall structure using the Seismic Performance Prediction Program (SP3) software. Casa Adelante is the first multi-family affordable housing building to be awarded a USRC Gold Rating. The estimated cost differential for the improved resilience was only a 0.25% premium over the total construction cost of a conventional building. The following paper provides steps for analyzing and designing a rocking mat foundation, and a graphical presentation of the modeling approach in CSI Perform 3D. Rocking mat foundation behavior, special design considerations, construction insights, lessons learned, and concepts for improving resilience in rocking buildings are also presented.

Introduction

Casa Adelante opened its doors to residents in January 2020. The project was constructed with a budget of $40.2 million. The design goal was to provide a resilient and high-performing building to protect and shelter-in-place the occupants in the event of an earthquake, without adding significant construction costs. The architectural rendering of the project is shown in Figure 1.

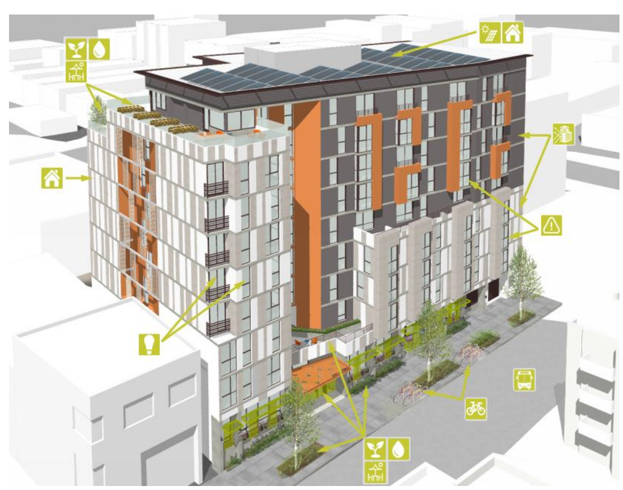

Figure 1 - Architectural rendering of Casa Adelante by Herman Coliver Locus Architecture

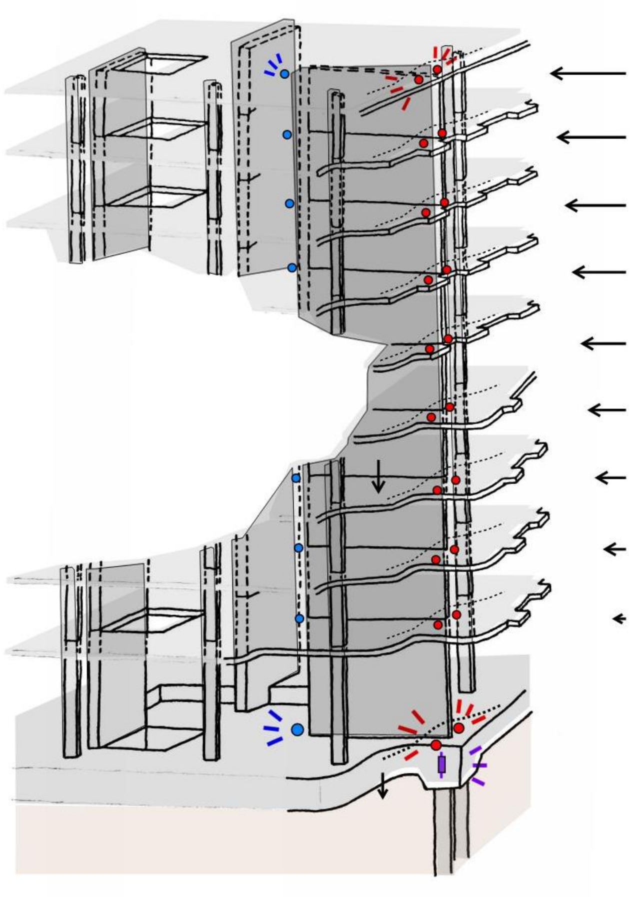

Figure 2 - Rocking mat foundation with plastic hinging in mat slab and superstructure slabs and supplemental damper yielding

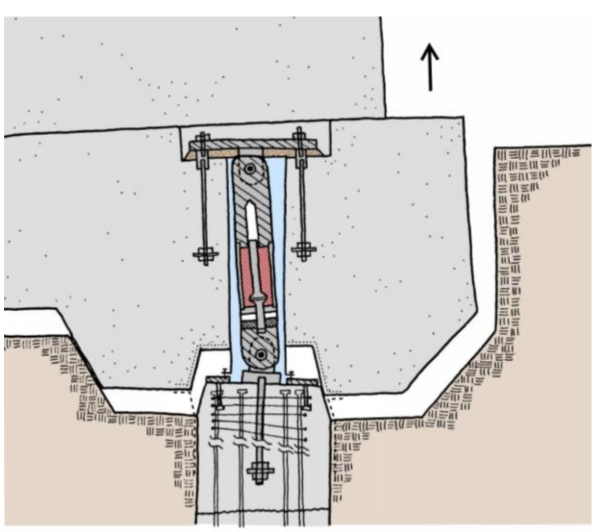

Figure 3 - Enlarged view at the lead extrusion damper during mat foundation rocking

The nine-story reinforced-concrete structure has a footprint of 135' x 75'and sits on a sloped site. The first story is 14'-0" high and the remaining upper stories are 8'-8" high. The gravity system consists of 8" thick concrete post-tensioned slabs, 14" square concrete gravity columns, and a 4'-0" thick reinforced concrete mat foundation. The building's lateral system comprises of approximately 16" thick, 20'-0" long, reinforced concrete shear walls over mat foundation. Due to architectural constraints, the shear wall configuration is three-sided, with three transverse shear walls spaced along the length of the building, and both longitudinal shear walls restricted to the center of the building, resulting in a torsional irregularity.

Instead of a conventional reinforced concrete shear wall system, the primary lateral force resisting mechanism was selected to be foundation rocking, with plastic hinging in the mat foundation. Under small to moderate levels of shaking, the seismic forces are designed to be resisted by the shear walls, acting with an essentially fixed base. The overturning resistance is provided by the self-weight of the structure and flexural strength in the mat. Under greater seismic motions, the shear walls and mat foundation rock in stable overturning. As the shear walls rock, the reinforcement in the superstructure slabs and mat slab yields, dissipating energy via inelastic deformations. Figure 2 shows the rocking of the mat slab at an interior transverse shear wall for an earthquake in the transverse direction. The two longitudinal walls are shown in the background. Negative and positive bending in the slabs at the ends of the rocking shear wall are shown using red and blue plastic hinges, respectively. Supplemental lead extrusion dampers also contribute towards the energy dissipation in the transverse direction. Figure 3 is an enlarged view showing the uplift of the mat slab at the lead extrusion damper.

This paper presents an overview of rocking building behavior, modeling and design procedures, insights gained throughout design and construction, and performance and resilience outcomes of this rocking mat foundation building

Selection of a Rocking Behavioral Mechanism

To achieve the goal of high-performance and low cost, efforts were focused on maximizing the inherent attributes of the building. The significant self-weight of the concrete mat slab and walls functions both as overturning resistance for the rocking mechanism, and as a self-centering feature during an earthquake. By allowing the foundation to rock, the untapped weight of the thick foundation and strength from the reinforcement in the foundation could be harnessed. A second attribute is in the strength of the superstructure slabs. The yielding of reinforcement in the superstructure slabs provides resistance, and the horizontal post tensioning provides an elastic restoring force if the building were to rock in an earthquake. Taking advantage of these inherent sources of strength through a rocking design eliminates the need for placing concentrated groups of piers at the ends of shear walls, that would otherwise be needed for a conventional design.

The decision to allow rocking is inherently tied to improved performance and resilience. Rocking systems typically comprise of walls or frames that uplift or rock about their toe during an earthquake. The building is protected from the damaging effects of earthquake shaking by the uplift, and the energy is dissipated in the back and forth rocking mechanism. Uniform deformations are forced along the height of the building through shear walls that act as stiff spines. The plastic hinges are localized at the slabs throughout the entire height, and story mechanisms are prevented. As a portion of the building's weight is lifted during an earthquake, the same weight helps restore the building to plumb after the earthquake. Therefore, rocking systems tend to have low residual drifts compared to most other systems. Keeping residual drifts low is essential for keeping residents in the building after a major earthquake.

Although not all rocking buildings have dampers, dampers proved to be critical at certain locations for Casa Adelante. At two locations where the shear walls in the transverse direction were close to the building property line, piers were required to resist the high compression loads at the toes of the rocking shear walls. In a conventional non-rocking design, pier tension reinforcement would be tied to the foundation to provide overturning resistance. However, the wall footings needed to rock. Additionally, if the pier reinforcement was anchored in tension, it would yield and not have reliable hysteretic behavior as it would tend to buckle under compression. To supplement uplift resistance at these locations, dampers were introduced.

Lead-extrusion dampers developed by Prof. Geoffrey Rodgers at the University of Canterbury, NZ were specified at the ends of the shear walls at the pier locations. In these lead-extrusion dampers, energy is dissipated when the shaft bulb temporarily plasticizes and displaces the surrounding lead as it moves in the cylinder. Figure 4 shows the damper at rest and in an elongated state. Each damper can elongate up to 9.5 inches and resist over 225 kips. These dampers do not need to be replaced after an earthquake and can be used repeatedly with a predictable hysteretic behavior. Figure 5 shows the hysteretic behavior and the force and displacement capacities of all four lead extrusion dampers used in the project. These curves are the results of a full-scale lab test done by Prof. Geoffrey Rodgers. For more information on damper behavior, design, and testing, see Aher et. al., 2018.

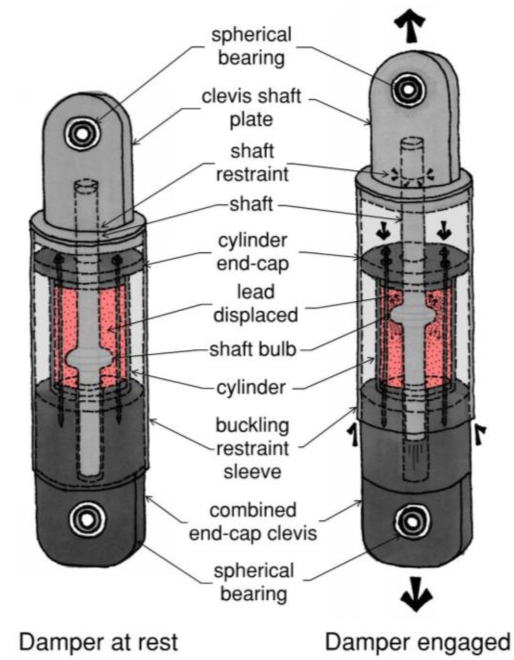

Figure 4 - Lead extrusion damper shown in an at rest and elongated state

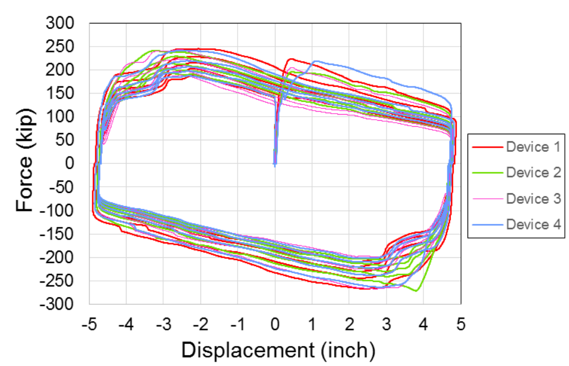

Figure 5 - Hysteresis behavior of the lead extrusion damper

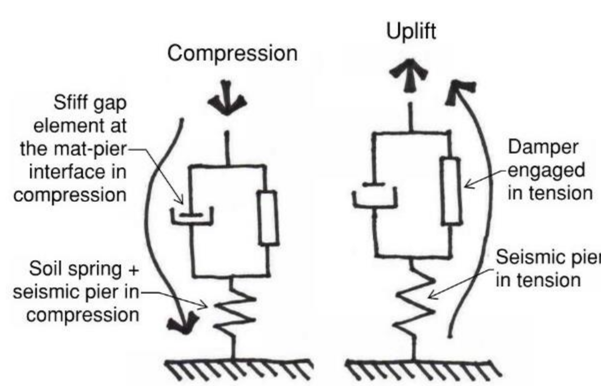

Figure 6 - Damper modeling in Perform 3D

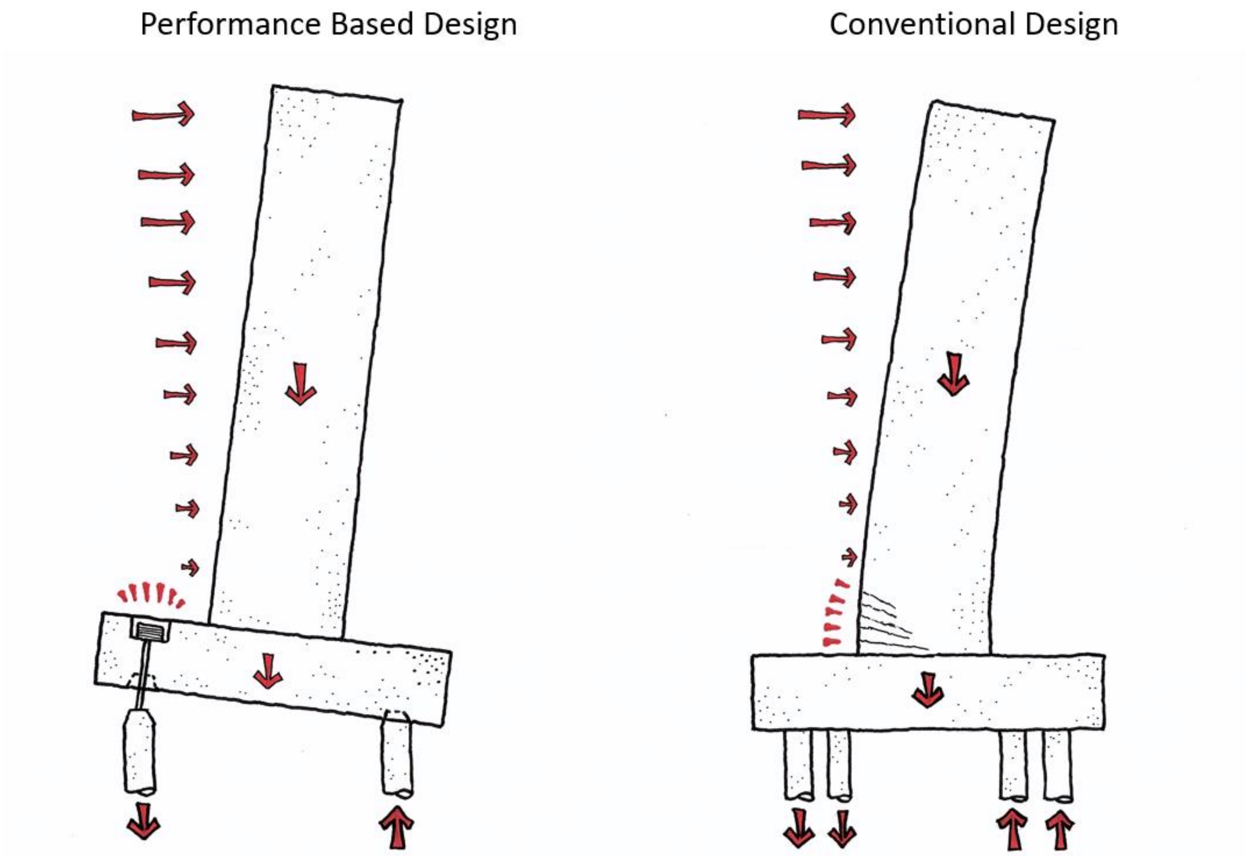

Figure 7 – A Performance based rocking foundation design versus Conventional shear wall design

Comparison to Conventional Design

To explore the feasibility of achieving a higher performing rocking building for a marginal cost differential, preliminary comparison studies were performed. To check the cost differential, an initial cost comparison study was performed between the rocking system and a conventional shear wall building. In the early stages of design, the preliminary lateral system was selected to be shear walls with rocking wall footings, see Figure 7. The cost of the resilient design was estimated by the general contractor to be similar to that of the conventional design. The resilient design had fewer piers and a thinner mat than the conventional design, which offset the cost of added dampers. To compare performance, an initial post-earthquake economic loss study was performed comparing the two options. The resilient design was estimated to be worth roughly $0.5 million more in net present value as compared to the conventional scheme, due to lower calculated seismic damage over its lifetime. Based on the positive outlook of these studies, the resilient design was recommended to the owners, developers, and the design team.

Steps for Designing a Rocking Foundation Building

Though design of rocking foundation buildings is unconventional and lacks a clear code-based prescriptive procedure, the basic design steps utilized for this project are described below to clarify the process.

First, the code base shear was calculated using an R-factor for a conventional concrete shear wall building. While there is no R factor for a rocking building, the code-level base shear can be calculated using a conventional R-factor to come up with a preliminary rocking design that will remain elastic for code-level forces. A rocking building is typically designed to stay linearly elastic at the code level forces, but will rock (dissipate energy through rocking and yielding) at an MCE_R level earthquake. In hindsight, a stronger and stiffer building, would have even better performance.

The base shear was applied at the equivalent height of the building, producing the minimum design overturning resistance. In a conventional design, the center of rigidity is desirable to be close to the center of mass to minimize torsion. In a rocking design, the center of strength (the non-linear strength at which the building rocks) is desirable to be close to the center of mass for a simultaneous rocking of all walls in that direction. The proportion of the total overturning moment to be allocated to each wall line was determined based on balancing the center of strength.

At each shear wall, overturning was considered in both directions, with the following steps to determine required mat slab and superstructure slab reinforcement. First, the overturning resistance provided by the building attributes were considered. Part of the overturning resistance was provided by the self-weight of the building and mat slab. Another part of the overturning resistance was provided by the horizontal post tensioning in the superstructure slabs. The gravity slabs had already been designed as post-tensioned concrete members and it was decided to tap into this strength for restoring action. Because of the unbonded post-tensioning, a net axial force from the post-tensioning is assumed at the center of the slab due to the effects of deadload balancing. As the wall rocks, this axial force generates a restoring moment at the slab-wall interface. The restoring moment is equal to the force from the tendons within a column strip at the end of the shear wall multiplied by half the slab height.

The remainder of the required overturning resistance was provided from the reinforcement yielding in the mat and the superstructure slabs. Using statics, the reinforcement for the mat and superstructure slabs was determined to meet the strength demand. In cases where gravity columns were located too close to the shear wall end or had insufficient gravity load to pin the mat down, the mat slab had to be designed to lift the column during rocking. Where adjacent interior columns had sufficient gravity load to pin the mat slab down, the mat reinforcement could yield in double curvature between the end of the uplifting shear wall and the column. In addition, interaction effects were considered between shear walls rocking simultaneously to verify that gravity loads were not double counted.

Once the slab reinforcement was determined for all shear wall locations, the preliminary design was input into a Perform model with expected material properties, evaluated with response-history analysis, and iterated to achieve a final design.

Perform Modeling

A non-linear model was built using CSI Perform 3D. All shear walls, mat slab, superstructure slabs and gravity columns were modeled, as seen in Figure 8. Currently, non-linear reinforcement yielding in the mat and superstructure slabs cannot be easily captured in structural analysis programs including ETABS, SAFE, RAM Concept, or COMSOL Multiphysics. In response to these limitations, the mat slab was modeled in CSI Perform 3D as a grid of strips with tributary cross-sections as shown in Figure 9. The building site was modeled with compression-only soil springs. The calculated mat slab reinforcement was input as plastic hinges at the ends of the strips. Expected strengths, strain hardening and cyclic degradation were captured in the model inputs. Areas of the mat slab that were not anticipated to participate in the rocking were modeled without the plastic hinges.

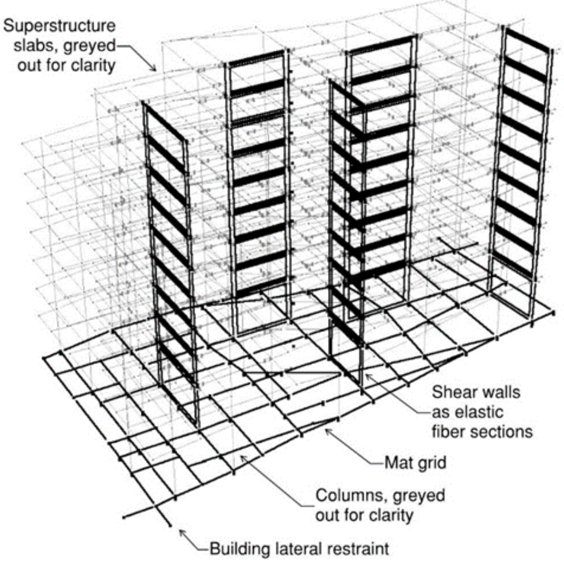

Figure 8 - Perform 3D model of the building

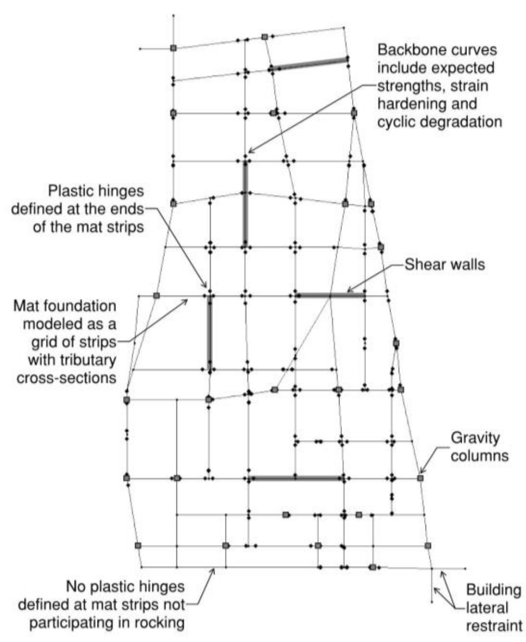

Figure 9 - Mat slab modeling

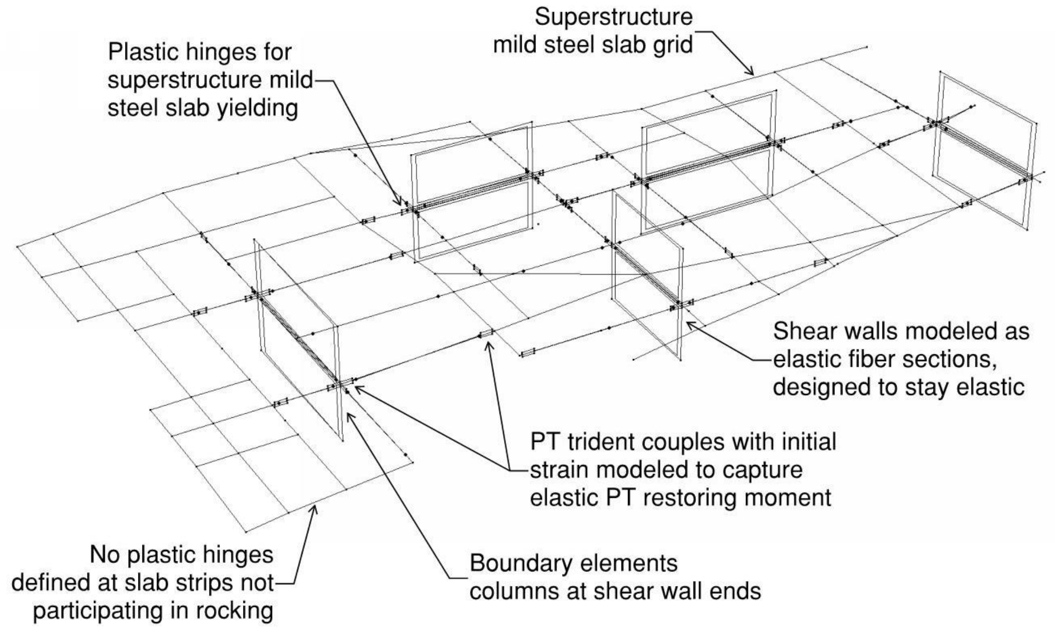

Figure 10 - Superstructure slab modeling

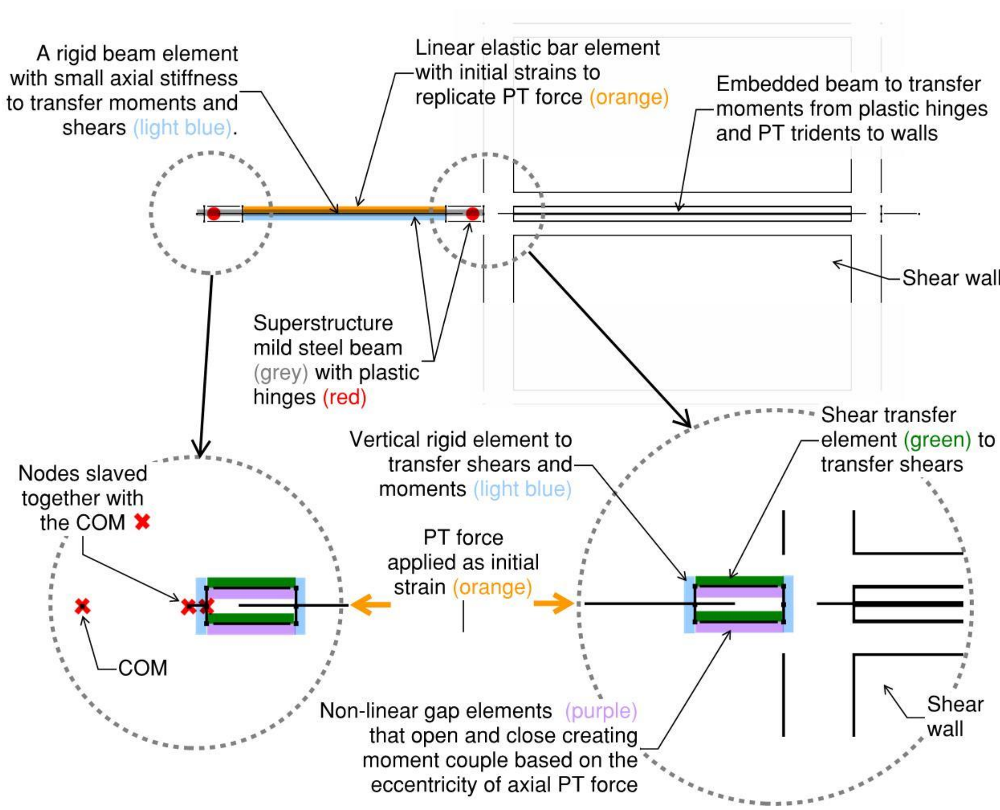

Figure 11 Post-tensioning trident modeling

The yielding reinforcement in the superstructure slabs was modeled like the mat slab, as seen in Figure 10. Non-linear elastic flexural hinges resulting from the post-tensioning reinforcement cannot currently be modeled directly in Perform 3D. To capture the non-linear elastic flexural hinge effect at the superstructure slab to shear wall interface, a two-pronged fork shaped assembly was created. The column strip post-tensioning force was applied as an initial strain to the assembly, resulting in an axial force in the two prongs modeled as compression-only gap elements. The restoring moment is produced from the eccentricity of the axial force as the gap elements in the prong open and close, reflecting wall rotation during rocking. The plastic hinge component from the mild steel reinforcement was accounted for with a parallel element between the two prongs. The entire assembly resembles a trident and is shown in Figure 11.

The shear walls were modeled as elastic fiber wall sections because the non-linearity was limited to the slabs. The damper was modeled such that when the mat slab uplifted, the tension flowed from the shear wall, through the damper, to the seismic pier. Similarly, as the mat fell back down, the compressive loads flowed from the shear wall, through the damper, to the seismic pier. After the mat returned to the ground, the compressive loads transferred directly from the shear wall to the seismic pier. The modeling of the damper and seismic pier assembly is shown in Figure 6.

Non-linear cyclic pushover runs were performed to validate the behavior of the non-linear components. Figure 12 and Figure 13 schematically describe the hysteretic behavior of the non-linear components for a typical rocking building. Understanding the global response, as well as the local response of each element provides a basis from which to validate the CSI Perform 3D output. The items shown include the hysteretic behavior of the entire building, mat and superstructure slab plastic hinges at shear wall ends, damper, seismic pier, gravity effects, post-tensioning, and soil springs. In each chart, different components and their hysteretic pushover curves are color coordinated and listed horizontally. For each component, the hysteretic behavior is defined as the building rocks back and forth. In each graph, previous steps are shown in grey for reference

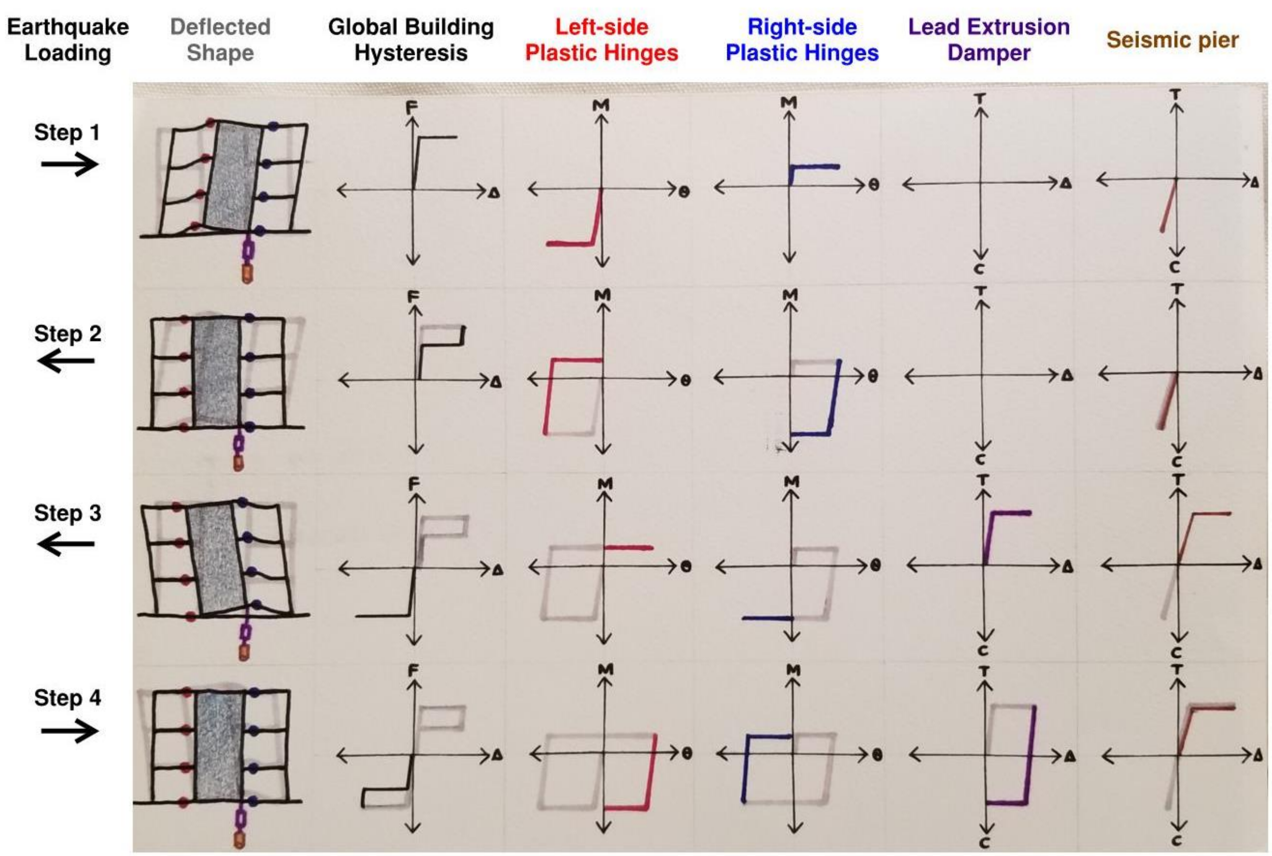

Figure 12 - Hysteretic behavior of non-linear components in a rocking building (Part 1)

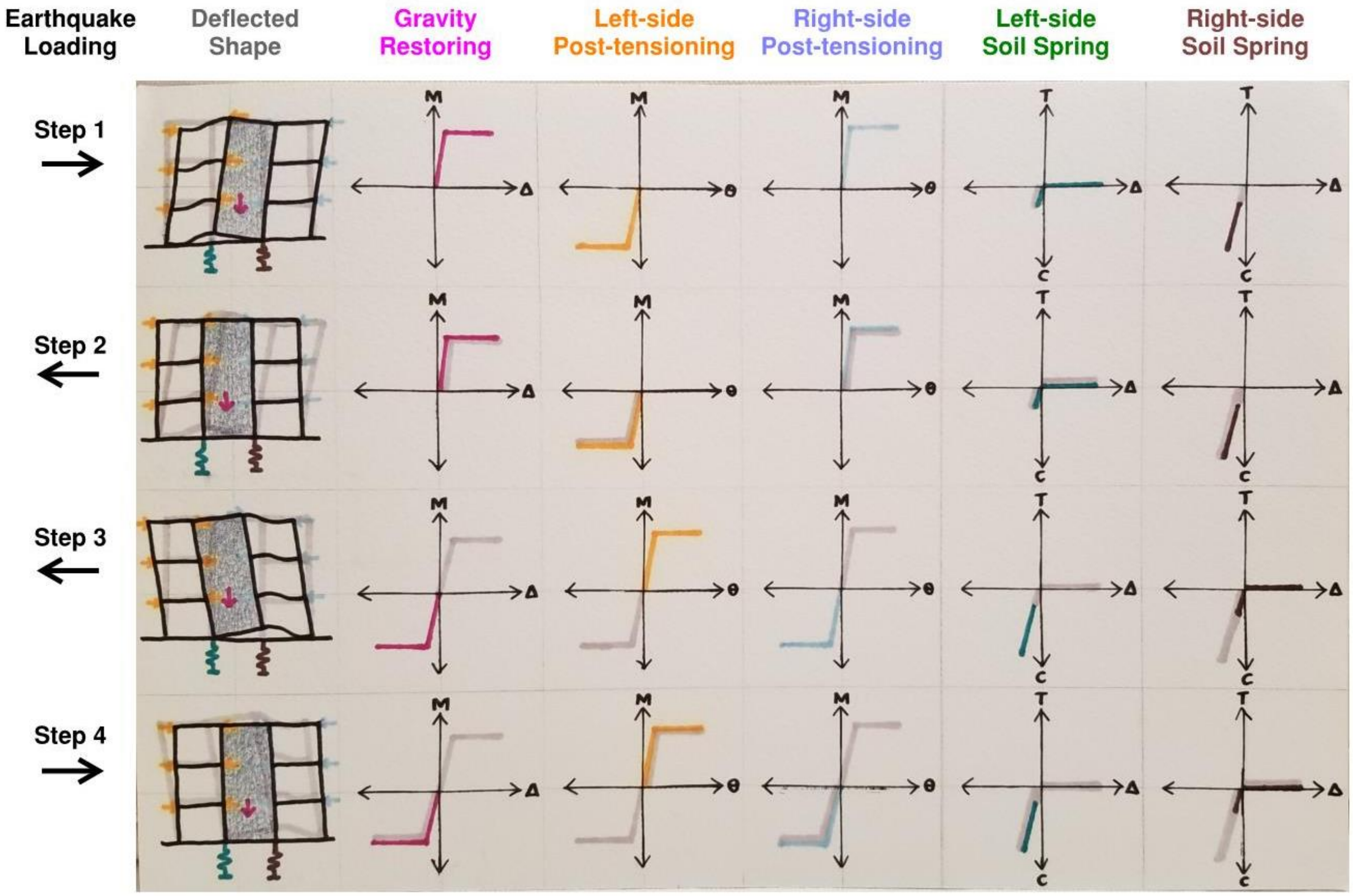

Figure 13 - Hysteretic behavior of non-linear components in a rocking building (Part 2)

To achieve a resilient design, the residual drift after an earthquake should be low. The building residual drift at the end of the response history analysis can be estimated by examining the global flag-shaped hysteretic pushover curve. Moreover, the balance of inelastic strength to elastic strength effects the potential for re-centering. A higher percentage of plastic strength relative to elastic strength increases the likelihood of residual drift. The design can be iterated during non-linear static pushover analysis to meet target building strength and reduce residual drift.

Design

The design of the building followed the PEER Tall Building Initiative (TBI). The model was developed using expected material properties with strain hardening. Sets of eleven records were used at the MCE_R and Service level earthquake.

Ground Improvement

The existing soil was susceptible to liquefaction and lateral spreading during a major earthquake. To improve the soil, the entire building footprint was strengthened using a grid of tightly spaced drilled displacement columns. Higher concentrations of drilled displacement columns were located under the shear walls to achieve higher bearing capacities based on soil pressure demand. The soil pressure maps were generated by modeling the mat slab in RAM Concept and superimposing reactions from the response history analysis.

Mat Slab Design

Response history analyses were performed, and the results were extracted to determine punching shear demands in the mat slab at the shear wall ends. Unlike a conventional shear wall, the total compressive force at the toe of a rocking shear wall is significantly higher. The toe carries the entire tributary weight in the wall, plus the uplift shear resistance from the slabs and the damper resistance at the lifting heel of the shear wall. This compression force is resisted by the soil spring reactions and shear resistance of the slab strips at the toe of the wall. The total tension force at the heel of the rocking wall is the sum of the mat slab shears and the damping force at the uplifting end of the shear wall.

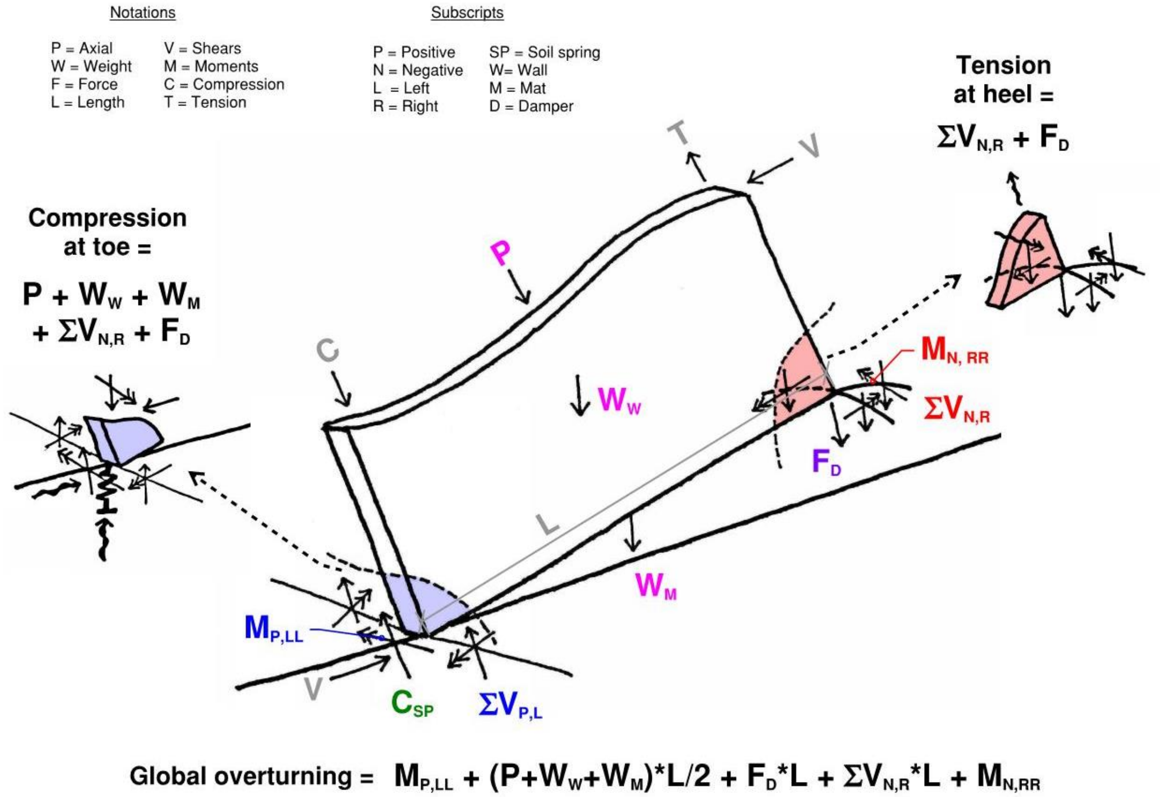

Figure 14 - Compression and tension reactions for a rocking foundation building

Figure 14 graphically clarifies the compression and tension reactions for a rocking foundation building. The negative moment (from a mat strip on the right, parallel to shear wall) and downward shear demands (from both the perpendicular and parallel mat strips) at the heel of the shear wall as the mat uplifts are shown in red. Similarly, the positive moment (from a mat strip on the left, parallel to shear wall) and upward shear demands (from both the perpendicular and parallel mat strips) at the toe of the shear wall are shown in blue. Gravity weights in the wall and the wall and mat slab self-weight are shown in pink. The damper force at the heel of the shear wall is shown in violet and the soil spring reaction at the toe of the shear wall is shown in green. These colors are coordinated with Figure 12 and Figure 13 for ease of reference.

The mat slab was designed for punching shear by providing a dense grid of vertical shear ties in the vicinity of the shear walls. The shear ties became sparse away from the shear walls, as the loads dispersed to the ground. The shear ties were T-heads at the bottom, with 180 hooks at the top for ease of placement. Mat slab reinforcement at the damper and seismic piers was designed using strut-and-tie principles.

In the mat slab near shear walls, the top reinforcing in both directions and the bottom reinforcing parallel to the shear wall were designed to yield during rocking. The bottom mat slab reinforcing perpendicular to the shear wall was designed to transfer the heavy compressive forces at the ends of the shear wall to the soil. Since the reinforcing was designed to yield at many locations in the mat and superstructure slabs, ductile ASTM A706 grade was specified throughout the project. Areas of mat slab away from the shear walls that were not involved in rocking were designed using RAM Concept.

Superstructure Slabs

The reinforcement in the superstructure slabs, like the mat slab, was designed to yield at the ends of the shear walls and iterated during response-history analyses to control torsion and drifts.

Columns

Columns were designed for the maximum shear demands resulting from $M_{p,}$ the maximum probable moment, of the column longitudinal reinforcement. Shear studs were provided in the superstructure slabs at every slab-column connection and at the ends of the shear walls to avoid shear failures in the superstructure slabs during rocking.

Shear Walls

Shear and flexural demands in the shear wall were obtained based on the response history analyses. In the event that the rocking mat slab had additional overstrength than what was analyzed and designed for, shear wall flexural hinging was designed as a back-up mechanism, with wall flexural demand capacity ratios of 0.95. Type 2 mechanical couplers were specified for the wall web and boundary reinforcement above the mat slab to control the reinforcement in the backup plastic hinge. High strength concrete and T-head crossties across the web of the shear walls were specified at the ground level to resist high shear and compression loads. At one longitudinal shear wall, the extents stopped at the corners of the elevator pit. To address this case, steel plates with shear studs were placed in the shear wall to transfer the high compression toe forces across the elevator pit to the rest of the mat beyond the pit, see Figure 15.

A more detailed design discussion can be found in Aher et. al., 2018.

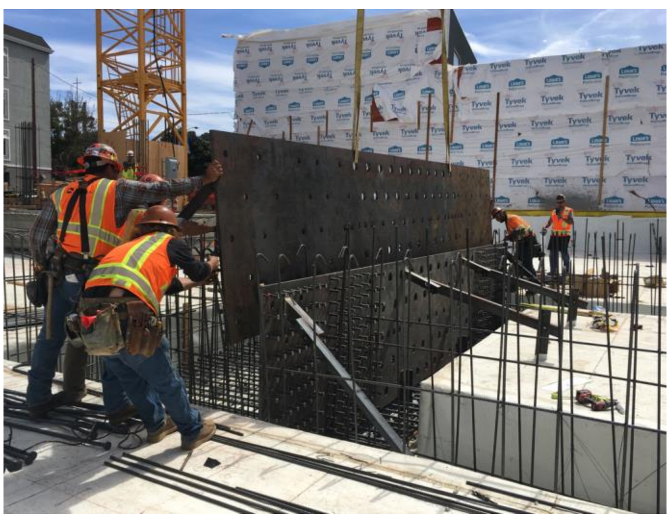

Figure 15 - Steel plates at the elevator pit

Additional considerations for designing rocking mat slabs

The dynamic nature of the rocking mat design required additional considerations to accommodate movement. A special waterproofing design was required by the waterproofing consultant at the damper locations. The waterproofing was attached to both the pier and the mat slab and was designed to stretch to accommodate the mat slab uplift (see dashed line in Figure 3). Special traversing rules were set for the plumbing in the mat slab to minimize damage from uplift, and the pipes were wrapped with 2 to 3 inches of compressible foam all around. Short height planter walls at the outdoor patios and ground floor retaining walls in contact with the columns were detailed with a gap filled with compressible structural foam around the column to avoid an accidental short column condition.

Drifts and displacements

The building drifts and uplifts are included for reference.

Peak and Residual drifts

The average MCE_R peak story-drift ratios at the building's corner points were 2.35% in the transverse direction and 1.47% in the longitudinal direction, within the PEER TBI limit of 3.0%. The corresponding average DBE level peak story-drift ratios were 1.26% and 0.81% respectively, and the corresponding average service level peak story-drift ratios were 0.46% and 0.25% respectively. For a reference comparison, the corresponding peak story drift ratios from modal response spectrum analyses were 0.97% and 0.68% respectively within the code limit of 2.0%.

The average MCE_R residual story drift ratios at the building corners were 0.43% and 0.15% in the transverse and longitudinal directions respectively, within the PEER TBI limit of 1.0%. The corresponding average DBE residual story drifts were 0.23% and 0.07% respectively, and the corresponding average service level residual story drift ratios were 0.05% and 0.02% respectively.

The peak and residual drifts in the transverse direction were the most difficult to control due to the torsional nature of the building. In contrast, the peak and residual drifts in the longitudinal direction were significantly lower than the PEER TBI limits. These relatively modest peak and residual story drift ratios resulted in low building damage and improved recovery time in the loss estimation studies mentioned subsequently. Seismic instrumentation was provided near the base, mid-height and top of the building to measure the actual building drifts during an earthquake.

Damper Displacement

The maximum and average MCE_R uplift demands at the damper at the base of the shear walls were 9.45 in and 4.9 in respectively.

Construction Insights

The complexity of the reinforcing in the rocking mat slab had to be translated accurately from design through to construction. The shop drawings required multiple rounds of detailed review. In the field, T2 heads and high strength rebar specified at critical locations had to be carefully inspected. Another aspect that proved challenging during construction was the common mindset is that more reinforcement is harmless, if not better. However, for a non-linear rocking system, the reinforcement in the zones of yielding needs to be deliberately limited to produce the desired behavior. Careful attention was needed during structural observation to ensure that only the appropriate reinforcement was provided. Where excess rebar had been placed, those bars had to be flame-cut.

Another challenge involved protecting the rocking mechanism from being unintentionally short-circuited during construction. A temporary shoring assembly was provided by the general contractor to support large steel plates at the shear wall near the elevator pit, as seen in Figure 15. If the shoring assembly was left in place during the concrete pour, it would have hindered the rocking mechanism. To avoid this possibility, the shoring had to be decoupled from the steel plates to allow the shear wall and steel plates to uplift as intended.

Additionally, careful coordination was needed with the plumbing and the electrical consultants to avoid certain zones for conduit placement in the mat and superstructure slabs. To coordinate the plumbing in the mat slab, a Building Information Model (BIM) was developed and detailed shop drawings were provided. These practices were effective in minimizing conflicts and field coordination. In contrast, the same was not provided for the electrical conduit placement due to contractor conventional practice, and the clearance rules had to be enforced as conflicts were discovered in the field. Emphasizing the need for BIM and detailed shop drawings proved very useful in coordinating with MEP trades

Lessons learned for future rocking designs

Over the course of designing Casa Adelante, several insights were gained which may assist other engineers designing rocking buildings. One lesson learned involves designing for low drifts early on. The peak and the residual drifts in the transverse direction were very difficult to optimize due to the torsional nature of the three-sided system. Although the building's nonlinear rocking strength was balanced to result in a torsionally stable non-linear pushover such that all shear walls rocked simultaneously, a torsional response was still observed during the response-history analyses. It was difficult to control the twisting, and the process of optimizing drifts became highly iterative and computationally time consuming, with each iteration based on response-history results. Minimizing torsional irregularity to control drifts and damage should be targeted early in the project with the architect's input.

In addition to torsional considerations, the strategic positioning of shear walls can help streamline the design. Positioning shear walls at least a bay width inside the building perimeter maximizes the gravity strength and restoring capacity compared to shear walls near building corners. In this project, both ends of one shear wall (Figure 2) landed at an elevator pit, resulting in a complex detail to transfer the high compression forces past the void to the rest of the mat slab. The alternative to locally increase the depth of the mat slab would have been similarly costly. Locating ends of shear walls away from voids in the foundation would help avoid complex and expensive details.

For maximizing reliable performance, lead extrusion dampers may be a good investment. These dampers perform more reliably than equivalent rebar in piers for a small cost premium. They essentially act as a yielding links that can accommodate large deformations without residual inelastic deformations. The devices are compact, with high capacity for axial loads. There appears to be significant potential for lead extrusion dampers in rocking building applications.

Figure 16 - Lead extrusion dampers being installed in the mat slab

To simplify design, it may be advantageous to use individual rocking shear wall footings instead of a mat slab, where locally deeper excavation is possible. Unlike the mat slab, individual shear wall footings would be relatively easier to design as they are isolated from interaction with each other.

Another lesson learned was to acknowledge and prepare for a higher likelihood of peer review when submitting a rocking design. In the plan check submittal of this project, a parallel code compliant design calculation package was submitted in addition to the performance-based design calculation package to streamline the review process. However due to the innovative nature of the design involving a rocking mat foundation and lead extrusion dampers, the San Francisco Building Department required a peer-review. The design team reached out to Prof. Greg Deierlein at Stanford to provide the peer review for the project. Submitting a code compliant design may not be sufficient for plan-check approval and it should be clarified early with the plan-checker if the innovative design will require a peer review.

Certain analytical capabilities could be valuable in modeling of rocking structures. The available structural analysis programs including CSI Perform 3D, ETABS and COMSOL Multiphysics currently have limited capacities to capture the non-linear reinforcement yielding behavior in the mat and superstructure slabs with simple modeling techniques. They also do not have components for directly modeling a non-linear elastic flexural hinge to capture the restoring effects of post-tensioning in the superstructure slabs. Though the behavior of these elements can be modeled indirectly, as described earlier, such efforts are time consuming. These capabilities, if incorporated in the existing analysis software could simplify future design efforts significantly.

Results

The construction for Casa Adelante started in June 2018 and the doors were opened to the public in January 2020. Figure 17 and Figure 18 show photos of the completed building. The construction was completed at a budget of $40.2 million within the construction time frame. A final cost comparison study was made between the rocking mat design and a conventional shear wall design with regular mat foundation. The cost premium for improved performance was roughly $100k, which was a 0.25% premium over the total construction cost of a conventional building. The pro-bono efforts of Prof. Geoff Rodgers to design and test the dampers, and Prof. Greg Deierlein to peer review the project are deeply appreciated.

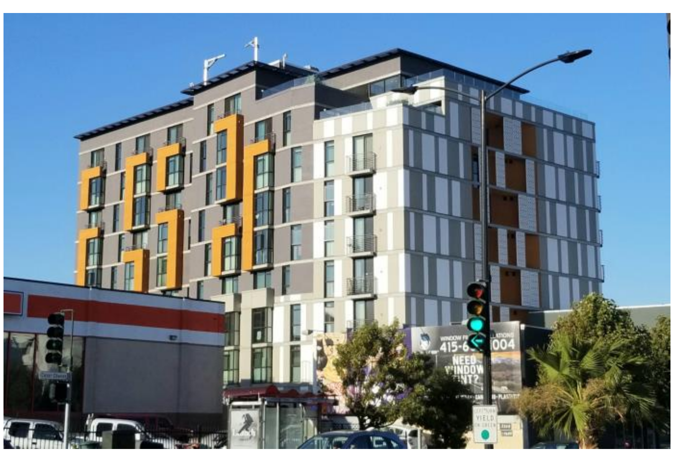

Figure 17 - Completed photo of the building

Figure 18 - Entrance to the building

Resiliency Results

Casa Adelante is the first multi-family affordable-housing building to be awarded a USRC Gold Rating, with 5/5 stars for safety and 4/5 stars for damage and recovery. The building's probabilistic risk-based loss analysis was done using SP3. The mean post-earthquake building repair cost as a percentage of the total building replacement cost is 6.6% for a 10% in 50-year earthquake and 25.5% for a 2% in 50-year earthquake. The REDi functional recovery time for a 10% in 50-year earthquake is in a matter of days without impedance factors, and less than 6 months with impedance factors.

There is an acknowledgement that both structural and non-structural repairs would be needed, on the order of days and weeks for functional recovery, and on the order of months for full recovery. The recognition is that given the limited alternative options available in San Francisco for sheltering after an earthquake, these local repairs would not prevent most of the building occupants from remaining in their homes.

Lessons learned for improving resiliency for rocking buildings

Drifts

Building peak and residual drifts are important contributors to damage in a building. To achieve high resilience, it would be desirable to aim for peak and residual design drifts much smaller than currently allowable code limits, and to target stronger, stiffer buildings right from conceptual design.

Design concepts for maximizing the elastic strength of a rocking building include:

- Adding vertical post-tensioning in the shear walls.
- Positioning the shear walls to maximize gravity tributary loads.
- Increasing the quantity and thickness of shear walls for higher elastic flexural stiffness.

- Architecturally optimizing shear wall placement to reduce the effects of torsion whenever possible.

Slab column connections

The repair of slab-column connections is a significant contributor to the cost of structural damages. During high drifts, thinner slabs tend to rotate more and crack at the column and wall connections as the building moves. Consequently, it is desirable to design these connections, keeping the punching shear demand-capacity ratios low, e.g. under 40%.

Strategies for enhanced slab-column connections include:

- Designing larger columns or thicker slabs where possible
- Adding shear studs at every column

Providing shear studs at slab-column connections is advantageous in improving drift (Megally and Ghali, 2000), reducing damage, and enabling post-earthquake repair. The shear studs can retain the integrity of the superstructure slabs during aftershocks. In addition, the slab-column joints can be repaired via epoxy injection after an earthquake.

Non-structural scope

The resiliency recovery time is often dictated by impeding factors and non-structural items outside the scope of the actual structural performance and direct repair time for the building. Impeding factors such as availability of funds and contractor mobilization could take many months. For tall buildings, elevator functionality is critical in considering re-occupancy times. The time needed to mobilize contractors to repair damaged elevators and MEP distribution systems may become a governing factor in determining the functional recovery time for a building. To mitigate the recovery time associated with damage to MEP distribution systems, the MEP consultants may be engaged early in the design. Certain non-structural components such as glass facades are typically not a concern in modern buildings as they are designed to accommodate high drift. In buildings with many interior partitions, partition damage could be widespread during an earthquake.

Conclusions

The design goal was to maximize the resilience of the structure given the construction budget. Casa Adelante was able to meet its design intent of improved performance and resilience at a cost premium of only 0.25% over the construction cost of a conventional building. This result would not have been possible without the teamwork of all those involved in the project and their efforts are deeply appreciated. It is hoped that this case study of Casa Adelante helps demystify the concept of a rocking building and provides a framework for analyzing, designing, and understand rocking buildings. Given the cost and performance outcomes of Casa Adelante, owners and designers may find encouragement and motivation to target higher performing designs with relatively low cost premiums, and improve the resiliency of a community after an earthquake.

Figure 19 - Visiting the completed Casa Adelante

References

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