

STRUCTURE

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JULY 2024

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The Hidden Value of a Deeper Structural Understanding

For many existing buildings, a targeted and more cost effective solution can be found through the use of advanced nonlinear analysis procedures.

By Jason Armes, SE; Gina Carlson, SE; and Leo Panian, SE

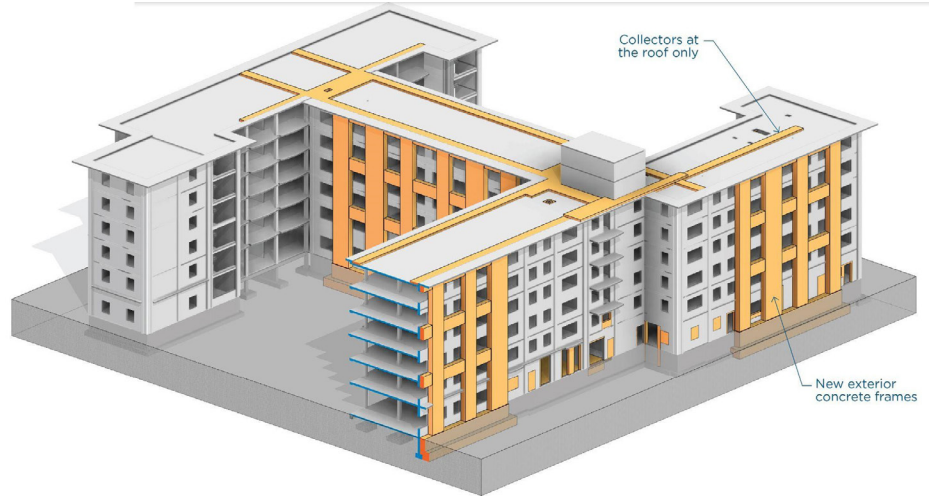
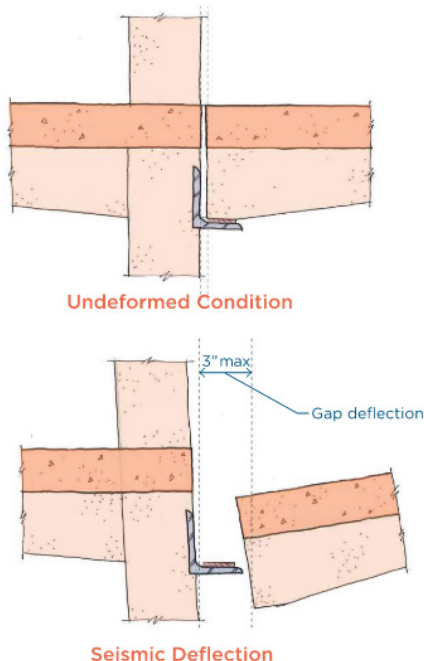
The poor performance of non-ductile concrete structures typically requires significant structural intervention to meet project seismic goals. Engineers usually take a linear analysis approach to assess building performance and provide a retro-fit, which can lead to high cost and a long, inconvenient renovation period. These extensive drawbacks make it challenging for the structural retrofit to fit within the project budget and broader goals.

To combat this negative outcome, Tipping took advantage of nonlinear modeling and analysis to provide optimized retrofit solutions for Hacienda Apartments in Richmond, California, a senior affordable housing complex. Nonlinear modeling and analysis provided a better understanding of the building's failure mechanisms and unlocked enhanced solutions that make the best use of the existing structure and add only what was needed to achieve critical performance. By leveraging both a linear and a nonlinear analysis, Tipping could make direct comparisons of the two and see how the project specifically benefited from a rigorous investigation into the behavior of the structural elements to provide improved, low-cost retrofit solutions that satisfied the building owner's needs.

Linear and Nonlinear Comparison

ASCE-07 & 41 both have two main analysis approaches, linear and nonlinear. Linear analysis is the traditional approach as it is well understood, easy to model, and quick to derive results. The seismic demands for linear analysis are generated with assumed stiffness of the material and then an applied factor to account for ductility. This would be the m-factor in ASCE-41 or the R factor in ASCE-07. These ductility factors are based on testing and real-world observations, but remain based on an archetype structure leading to conservatism in their approach.

Alternatively, non-linear analysis tracks the actual material and element yielding, hardening, and weakening of the materials during a seismic event. This analysis requires more up-front time in the initial model setup, additional time to process and refine modeling, and often a third party peer review. This process can leverage the entirety of the structure's existing strength, and unique structural solutions can be uncovered. In the right building, such as the Hacienda Apartments, this deeper understanding can lead to a targeted retrofit that has huge benefits for a project.



Above: The Hacienda Apartments' original structure is shown in gray, with the new elements in orange.

Left: Without the collector tie, the seat at the building joints of the Hacienda Apartments would be inadequate to support the gravity loads under seismic movements. This condition was addressed by tying the buildings together only at the roof level rather than at each floor, which saved considerable costs.



Concrete overlays are painted in white at the completed Hacienda Apartments. (Photo Credit Pyatok)



The Hacienda Apartments is a 150-unit complex built in 1964, before modern seismic building codes were developed. (Photo Credit Pyatok)

Case Study

Both linear and nonlinear analyses were performed and brought through detailed design for the Haciendas Apartments project. Both options provided acceptable solutions, but the nonlinear provided critical project benefits that allowed the retrofit to be less costly and invasive.

The Hacienda Apartments is a 150-unit, 121,000 square-foot complex that served as low income senior housing for decades, but became severely deteriorated due to neglect. The complex consists of four structurally independent six-story, mild steel reinforced non-ductile concrete structures built in 1964, before modern seismic building codes were developed. Each building is rectangular in plan and configured to have an open-air walkway on one side and concrete walls on the other three.

Each building is constructed with 6.5-inch thick, two-way spanning concrete floor slabs supported by beams and columns at walkway edges, concrete columns spaced at 15 feet on center within the building interior, and concrete walls at the building exterior. The foundations consist of grade beams and isolated footings founded six feet deep to avoid expansive clay site soils.

Each building's lateral force resisting system consists of 8-inch to 10-inch thick concrete walls. In the transverse direction, the buildings have solid continuous walls every 45 feet. The exterior longitudinal walls or perforated walls create a typical pier and spandrel beam system due to the multiple openings.

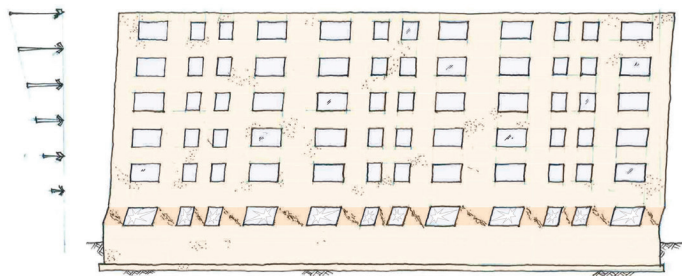
Given construction standards of the time, these structures present seismic performance issues such as insufficient gaps between buildings, floor slab bearing ledges susceptible to unseating, brittle seismic response at the perforated walls due to lack of confinement, foundation uplift and soil compression failures, and insufficient diaphragm connections to shear walls.

LDP Results

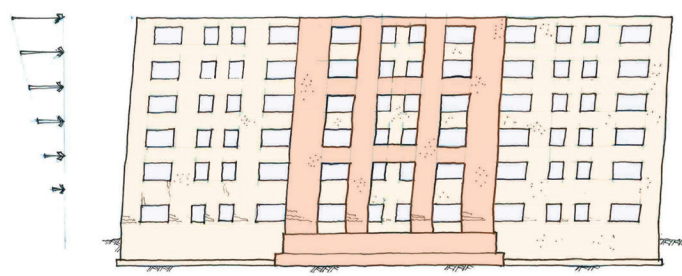
In the Design Development phase, a Linear Dynamic Procedure or LDP analysis (equivalent to an RSA in ASCE 07) was performed in ETABS. All perforated walls and solid walls were modeled using ACI cracked section recommendations, the foundation was pinned per ASCE allowances, and a distributed mass on the typical floors was used.

The results of the analysis indicated that the existing structures' relative movement was too great, and unseating of the slab at the corbels would occur. Additionally, demand/capacity ratios for the perforated and solid walls showed that they would be severely overstressed and sustain significant damage. Under these loads, the foundations were also overloaded and prone to large movements—suggesting larger spread footings or a deep foundation system would be needed.

Adding enough stiffness to prevent the existing corbel seismic joints between the buildings from failing was not practical. To eliminate the likelihood of this catastrophic failure, the buildings were tied together at each floor and at every joint with steel collectors and a steel shear



The original building was susceptible to nonductile concrete shear failures in the existing concrete piers leading to weak-story failures and concentration of damage.



With a new mode-shaping spine, the exterior concrete frames shape the mode of inelastic deformation and reduce the expected seismic damage by eliminating weak-story behavior and harnessing the strength of the existing structure.

link to make the buildings behave as one large building. To limit the stress on the existing walls, six 15-inch by 24-foot planar walls and four 24-inch by 50-foot shotcrete panels were overlaid to the existing wall to reduce the demand capacity ratios (DCRs) on the existing walls to the ASCE-41 acceptance criteria. The new walls were supported by large spread footings to ensure the soil bearing was acceptable.

A detailed set of plans and calculations for the design of seismic improvements, using the LDP was submitted to an independent peer reviewer in order to verify that the project met the necessary criteria. The intent was to meet the basic performance objective for existing (BPOE) buildings, as defined by ASCE 41, which is consistent with a Collapse Prevention (S-5) level of performance under the BSE-2E (~75% of MCE) hazard and the Life-Safety (S-3) level of performance under the BSE-1E (~75% of DBE) hazard. The criteria was established to meet the requirements of insurers and lenders for asset protection

This review showed the design approach was sound and supported the intended path forward. However, as the project proceeded through design, the project's construction budget for the affordable housing development was outside of the available funding. A large portion of this was the structural retrofit and the added cost to mechanical/interiors due to the extensive network of collectors. Significant cost savings were needed for the project to remain viable.

NDP Results

It was at this point that a nonlinear dynamic procedure (NDP) was leveraged to explore the possibility using insight from the more detailed approach to optimize the design and reduce the cost of the seismic improvements. A Perform 3D model was set up with all lateral elements modeled inelastically. Pier and spandrel elements represented the perforated walls with shear hinges, flexural hinges at the spandrels, and fiber section at the piers. The walls used inelastic shear and flexural elements. Additionally, inelastic collector elements and gap hook elements at the building joints were used to monitor the seismic joint. Existing and new foundations leverage soil springs to model soil yielding. All element and material properties used ASCE-41 recommendations and 11 ground motions were selected and scaled to match the target spectrum for the site.

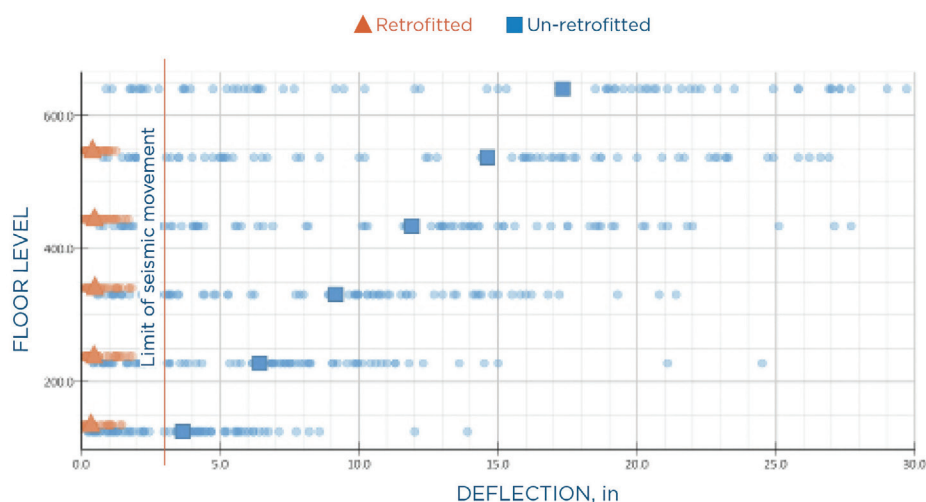
The analysis showed that the existing perforated walls had significant strength and stiffness, but were prone to a brittle shear failure in the piers at the first floor. It was also

observed that allowing some foundation flexibility showed a ductile rocking and flexural yielding mechanism in the larger planar walls. The perforated wall foundations were also found to be acceptable with soil flexibility. These observations allowed for the elimination of five of the 15-inch planar walls without overstressing the existing perforated or planer walls. Exterior overlays of the one planer and four perforated walls were kept to provide a mode shaping mechanism. This removed the brittle first floor shear failure and allowed flexural yielding throughout the existing wall providing a ductile and reliable mechanism.

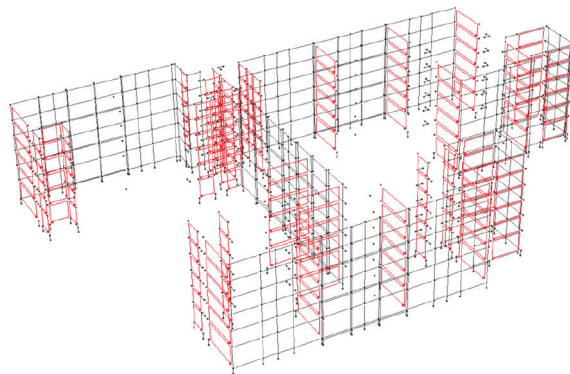
The model also monitored the existing shear hinges at all levels. It was observed that collectors at the roof were attracting the most load. A study was performed with collectors only at the roof to see if the existing structure and added overlays were stiff enough to prevent the seismic joints from exhausting their allowable movement. The roof collectors were found to be sufficient, and collectors could be removed at all other floors. MCE ground motions were run to ensure the roof collectors and seismic joint movements were reliable. Through this process, Tipping confirmed that no ground motions exceed the collector design capacities or allowable movement of the joints. The collectors were placed on the roof of the building to separate the retrofit work from the interior work.

The application of advanced nonlinear analyses resulted in a tailored and optimized set of highly effective and cost-efficient seismic improvements for the vulnerable non-ductile concrete structure. The solution significantly reduced the cost of construction by fully harnessing the strength of the existing concrete structure, taking advantage of rocking foundations to reduce foundation demands,

Seismic Separation Joint Deflection



The nonlinear analysis showed that collectors only at the roof level would effectively tie the building together and reduce the deflection at the separation joint to maintain integrity of the support in a large earthquake.



and linking the structures together only at the roof, rather than at each floor level. This solution would not have been possible without detailed shaking simulations and relying on simpler linear-elastic elastic methods.

Why It Matters

Ultimately, the structural engineering solution was a key component of making the affordable senior project viable by preserving and making the best use of the existing structure. With the LDP retrofit approach, estimates for the seismic retrofit were at \$4.63 million and the targeted improvements and optimized approach were priced at \$3.9 million at bid, allowing \$730 thousand to be reallocated for other important project elements.

Secondary benefits included simplifying MEP coordination, coordinating architectural finishes, and limiting trade overlaps in interior areas by having the seismic retrofit only on the exterior of the building. This also allowed the seismic work to proceed simultaneously with the interior construction, significantly reducing the construction duration.

The insights of the NDP allowed these benefits to be leveraged and the moderate additional design fees and design time were more than offset with the benefits during construction. NDP made an innovative structural solution possible and brought a deteriorating complex back to life to once again provide safe, affordable housing for local seniors. ■

Top right: The nonlinear dynamic analysis model provided critical insight into the structure behavior. This approach eliminated the need for collectors at five of six floors, five new full height shear walls, and micropile deep foundations.

Above: Reinforcement cages of concrete overlays are located at perforated walls

Project Team

Structural Engineer: Tipping

Architect: PYATOK

Owner/ Developer: Mercy Housing California

Contractor: Nibbi Brothers

Peer Review: Charles Thiel, Telesis Engineers

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