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Optimization framework to support recovery-based design of buildings—preliminary results

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ABSTRACT

Developing interim building provisions for functional recovery will require communities across the United States to select appropriate target times and hazard levels for various classes of buildings. This paper presents an optimization framework to support the design of structures for functional recovery and isolate optimal performance enhancement solutions considering stakeholder priorities (such as added cost, aggregate capacity increase (α), construction days added, etc.) subject to achieving specific target recovery times. The framework is applied for a pair of modern, 3-story welded steel moment frame (WSMF) office buildings ($I_e = 1.00, 2.00$) in Oakland, CA, with a target time T_{target} of 14 days at the design-level earthquake, and a tolerable probability of exceedance of 50%. We find that when using nonstructural component enhancements and real-valued genetic algorithms, we are able to reliably isolate the α-optimal suite of component capacity improvements. While model A ($I_e = 1.00$) generally requires larger capacity increases for SDR-sensitive components, model B ($I_e = 2.00$) necessitates larger capacity increases for high-quantity, acceleration-sensitive components. Key benefits of the framework include that it (i) implicitly quantifies the effectiveness of various performance enhancement strategies, and (ii) can provide new metrics of structural and nonstructural component importance across stakeholder-specific priorities.

Introduction

A recent study by the Federal Emergency Management Agency (FEMA) [1] found that 20-40% of modern code-conforming buildings would be unfit for reoccupancy following a major earthquake (taking months or years to repair) and 15-20% would be rendered irreparable. In recent years, functional recovery has been proposed [2-4] to replace life safety as the baseline performance target for new buildings in the United States. Buildings designed for functional recovery would be required to recover their basic, tenant-specific functions in target time T_{target} for a user-defined seismic hazard. A committee of experts [4] has recently recommended to Congress that communities at the local, state, and federal level determine these target times and hazard levels for schools, hospitals, residences, and other occupancy types. While this goal-setting is a critical step toward resilience-based engineering provisions, little research has been done to support community-specific decision making. This paper summarizes and applies a proposed optimization framework to support the design of structures for explicit recovery targets, which can be tailored to specific buildings, site conditions, and recovery targets.

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Overview of framework

To apply the proposed framework (Fig. 1), (1) a site is first selected, a building is designed in accordance with current code objectives (i.e., ASCE 7), and a baseline recovery performance assessment is performed. Recovery performance is evaluated by first applying the FEMA P-58 methodology [5] to obtain component-level damage and repair time metrics. These results are then used as inputs to a downtime assessment [6, 7], which uses repair sequence logic to estimate the functional recovery time, considering various impeding factors such as inspection, financing, design, and contractor mobilization. The selection of the downtime assessment method should be based on the desired repair sequence logic and compatibility with the building of interest.

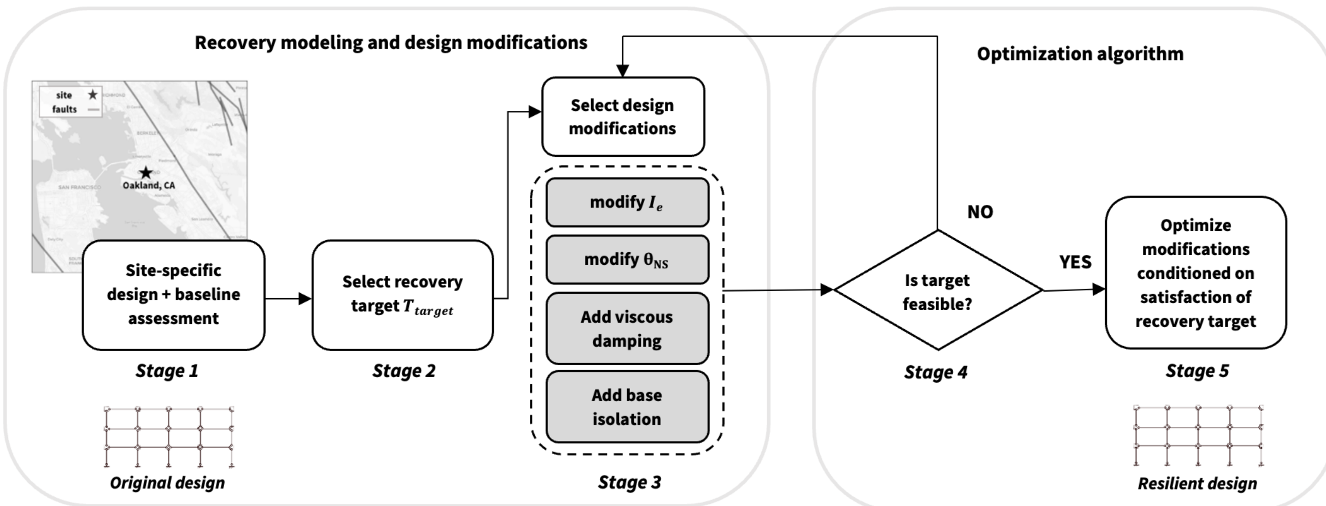

Figure 1. Proposed optimization framework, starting from code-based design.

The objective of recovery-based design is to limit the probability of exceeding a particular target time to a defined threshold, subject to a seismic hazard of level of interest [3]:

$$P\left(T_{FR} > T_{target}\right) < Y\%, \text{ given } D_{FR} \quad (1)$$

where T_{FR} is the building's estimated functional recovery time and D_{FR} is the selected hazard level. Therefore, in next stage of the framework (2), T_{target}, Y and D_{FR} are selected based on community-specific goals, as highlighted in the Introduction section. The selection of Y will determine the p-percentile functional recovery time to compare with the target.

Next, (3) design modifications are reviewed and selected with the objective of closing the recovery gap, which is the time differential between the p-percentile baseline recovery time and T_{target}. Example modifications include more robust structural and nonstructural components and systems, as well as the addition of base isolators and viscous dampers [3]. Collapse risk and irreparable residual drift may hinder the ability for certain options to effectively reduce downtime at the selected value of Y. To address this, (4) a feasibility check is performed to ensure that the design modifications selected can close the recovery gap. If not feasible, (3) will be repeated as necessary.

Finally, (5) an optimization routine is performed to determine optimal design solutions that satisfy the recovery target. Examples of the objective function include total cost-of-enhancement, aggregate capacity increase, and cumulative construction days added. The choice of the optimization strategy is dependent on the inputs to the objective function, as well as computational constraints.

Case study

This case study considers a pair of modern, 3-story welded steel moment frame (WSMF) office buildings located in Oakland, CA (Fig. 2). In this example, T_{target} is set to 14 days at the design-level earthquake (475-year return period), with a tolerable probability of exceedance of 50%. We refer to the archetypes as model A ($I_e = 1.00$) and model B ($I_e = 2.00$). In this example, we are interested in the effectiveness of various nonstructural component enhancements, independent of cost.

Each WSMF building archetype is designed in accordance with ASCE 7-16, under Site Class D conditions. Both the design and analysis of the archetype is performed using the Auto-SDA platform [8], which develops code-conforming steel structural models in OpenSees [9]. Next, site-specific ground motions are selected for use in nonlinear analysis. In this case, the 2011 PEER Transportation set [10] is leveraged, which consists of 40 pre-selected ground motions to match the uniform hazard spectrum and associated causal events at the Oakland site. The structural model is then subjected to these records to generate a set of engineering demand parameters (EDPs), consisting of peak-floor accelerations (PFA) and story drift ratios (SDR).

The FEMA P-58 methodology, applied in Stage 1 of the framework, is performed using the NHERI-SimCenter Pelicun platform. The ATC-138 (Beta) methodology downtime assessment procedure is used [6], since its estimates of functional recovery time account for the interaction between different system-specific components in the building. Neglecting impeding factors, the 50th percentile recovery gap for model A and B is similar in duration, at 42 days and 40 days, respectively. We select nonstructural capacity improvements as the sole enhancement strategy to eliminate each gap.

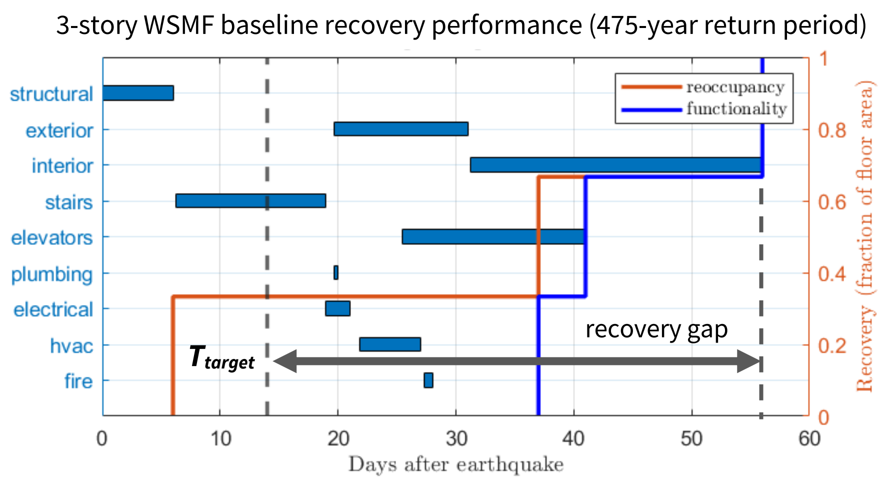

Figure 2. System-level Gantt chart for the 50th percentile realization of recovery (model A).

Since collapse and irreparable drift do not impact recovery times at the 50th percentile in both cases, we can proceed to Stage 5. Using real-valued genetic algorithms [11, 12] as the optimization procedure, we define the input $\boldsymbol{x}$ (Fig. 3a) to be a vector of parameterized scales that increase the median capacity (θ_{DS}) of nonstructural components across all damage states. The objective function is defined as:

$$f(\mathbf{x}) = C(\mathbf{x}) + \rho\left(T_{FR,50} - T_{target}\right)^2 \tag{2}$$

where $C(\boldsymbol{x})$ represents the cost term, and the second term is a quadratic penalty on solutions that do not satisfy T_{target}. The magnitude of the penalty is defined by ρ. In this example, $C(\boldsymbol{x})$ represents the aggregate capacity increase α across $\boldsymbol{x}$, since we are interested in solutions which capture components' intrinsic ability to shorten the repair schedule, independent of cost.

Results

An α-optimal solution is generated for both WSMF models in the case study to explore the impact of the importance factor on the necessary nonstructural component enhancements. An enhancement for the i^{th} component is performed by scaling θ_{DS} by x_i (Fig. 3b).

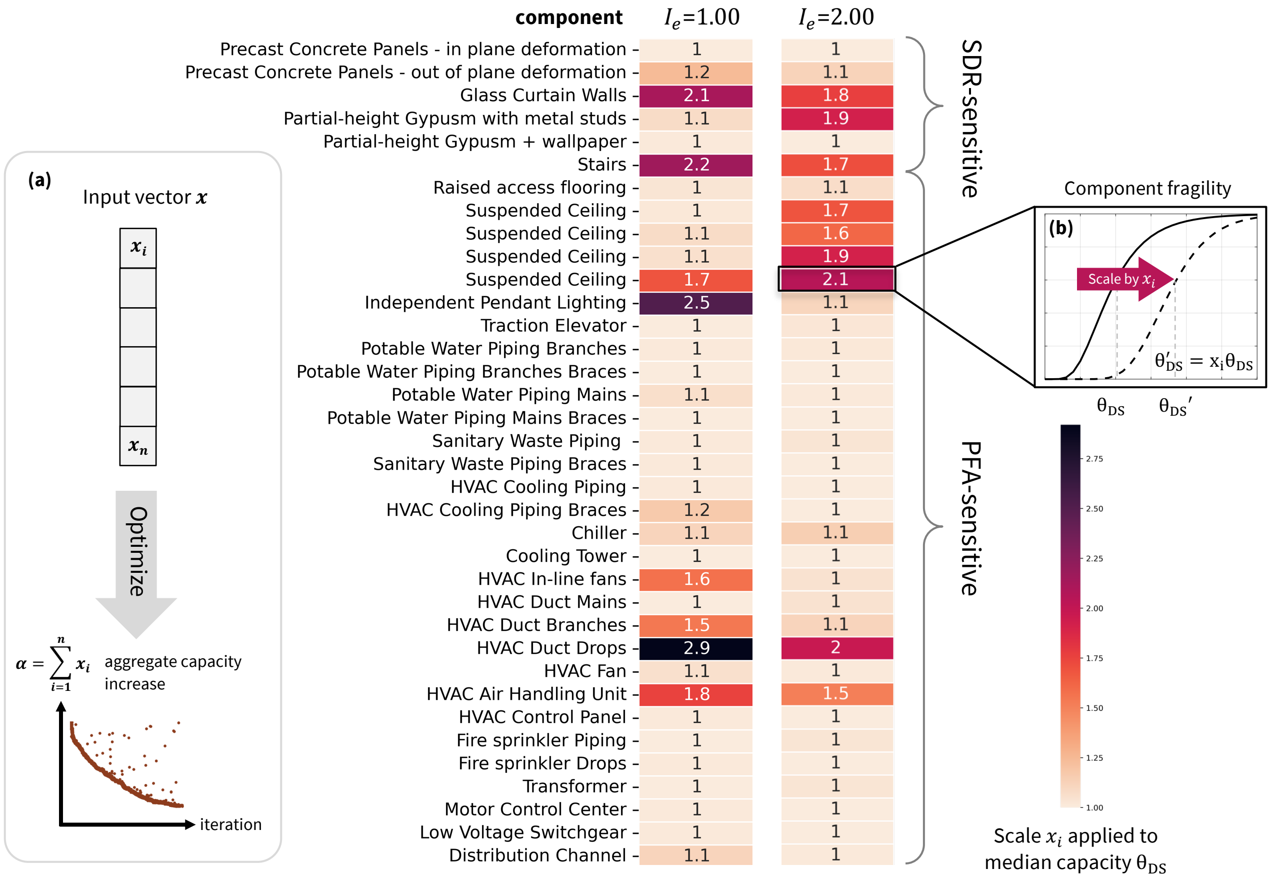

Figure 3. The α-optimal nonstructural capacity improvements to achieve a 14-day median functional recovery time ($T_{FR,50}$) for model A ($I_e = 1.00$) and model B ($I_e = 2.00$).

The α-optimal set of enhancements differs for each building. Model A incurs greater greater story drifts across all three stories, so a number of SDR-sensitive components will require larger capacity increases (larger x_i values) than those in model B. On the other hand, we find that the larger I_e for model B (and hence, stronger accelerations on the upper stories), translates to larger capacity increases for some PFA-sensitive components, such as the suspended ceiling. Overall, each value of x_i in Fig. 3 translates to an actionable measure of component importance that can be used directly in subsequent design iterations. By optimizing α, these design solutions reveal the nonstructural component modifications (accounting for intra-system interaction) that are most effective at achieving $T_{FR,50}$. This analysis can be re-performed using a cost-based objective function to investigate how these solutions change when cost-of-enhancement is considered.

Conclusions

Communities across the U.S. will soon determine recovery targets and associated hazard levels for various classes of buildings and occupancies. To support their decision making, this research couples state-of-the-art recovery modeling with optimization methods to facilitate recovery-based design. In addition, the framework can be used to (i) quantify the recovery performance of buildings designed to current provisions, (ii) provide building- and site-specific insights into the optimal enhancements necessary to eliminate recovery gaps, and (iii) develop new component- and building-level metrics that can be used in policymaking and design.

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An academic license of the SP3 software (www.sp3risk.com) was used in the performance of this work.

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