

Expected Performance of New Building-Code-Compliant Buildings in California

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Abstract

The Building Code aims at ensuring safety (non-collapse) in the event of a large earthquake; both research and the sentiment in the Structural Engineering profession is that the Code is expected to meet this safety goal well. However, the Building Code does not have a primary aim of preventing damage, limiting building closure times, or limiting financial losses (for typical occupancy buildings, excluding occupancies like hospitals).

This paper looks at the level of performance the Building Code provides using the measures of building closure time and repair cost. The performance of new buildings located at a set of cities around California are compared and it is shown that the current design approach results in safe but disposable buildings. There is desire to build buildings better in California, such that buildings can be immediately occupied and used after an earthquake. To this end, buildings designed as critical facilities and specifically for resilience are also examined.

This paper is written for audiences interested in better understanding the expected seismic performance of new code-compliant buildings in California, with language provided for both non-engineering and engineering audiences.

Introduction

Through the years, the Building Code has changed to better achieve the goal of life safety. Through these iterations, the damageability of buildings has improved but this has been a secondary outcome. Although some types of buildings, e.g. critical facilities, are designed with performance goals in mind, the current Building Code is generally expected to provide

buildings that are safe but expensive and time consuming to repair, assuming that repair is possible.

Shifting design procedures to target performance in terms of repair cost and recovery time is possible and has been done in some recent designs with very little additional investment (Haselton et. al 2018). This study examines the performance of code and beyond-code buildings and recommends next steps to shift toward more resilient design approaches.

Method

The seismic performance predictions in this paper are based on the comprehensive FEMA P-58 Analysis Method (FEMA 2012) and the complimentary Resilient Design Initiative (REDi) Guidelines (REDi, 2013).

The FEMA P-58 Analysis Method is a rigorous building and site specific seismic loss assessment method based upon the performance-based earthquake engineering framework developed by the Pacific Earthquake Engineering Research Center (PEER), (Moehle & Deierlein, 2004). The results are provided in probabilistic terms and are broadly accessible to the general public and engineers (repair cost, repair time, and occupant safety), providing common ground for communication around resilient design and planning.

The REDi Guideline provides a more realistic way to look at repair time and downtime. Where repair time is the time required to make building repairs and downtime is the time for repairs as well as the impeding factors (actions that must occur before repairs may begin), these include building inspection and contractor mobilization, among others.

The analyses for this study were run using the SP3 software (SP3, 2018).

Analysis Results for Performance of New Code Buildings in California

In this study, the direct repair cost and functional downtime are examined for new buildings in California. Direct repair cost includes only the cost to repair or replace the building; indirect costs such as loss of production in the case of a factory or cost to find alternate housing in the case of a residence are not considered. The functional downtime represents the time from the seismic event to the time that the building may resume its normal function; in the case of a business, this requires that the structure is sound and the systems like the HVAC and water work, but the cosmetic repairs may still be incomplete.

Performance of an Example Building in Northridge California

Figure 1 provides the repair costs and building closure times for an example 8-story steel special moment frame building in Northridge California, designed according to ASCE 7-10, at two different levels of earthquake shaking. For a 475 year earthquake, the computed building closure time is ~8 months and the repair cost is ~15% of the building value. For a 2475 year earthquake, the computed building closure time is over a year and the computed repair cost is ~50% of the building value (making it likely that the building will be demolished rather than repaired, FEMA 2012).

To generalize these findings beyond this example 8-story building, similar analyses have also been done for taller buildings (though not examined in detail in this paper). Downtimes in taller buildings can be much longer, because there is more to repair; a recent study of a 40-story building shows up to two years of downtime for the 475 year earthquake. Conversely, downtimes tend to be shorter for smaller buildings.

Performance for Selected Cities in California

Figure 2 shows the repair costs for the same new 8-story steel special moment frame, but redesigned for 12 different California cities. Figure 2a represents losses for a 475 year earthquake, with resulting repair costs from 5-25% of the building value. Figure 2b represents losses for a 2475 year earthquake, with repair costs from 10-80% of the building value.

The difference between performance at various locations come from the effects of seismicity level (higher seismic sites generally have higher losses) as well as the relationship between seismicity and the level of shaking for which the building was designed. Probabilistic hazard shaking values (e.g. the 475 year shaking) from USGS are used to determine the losses in a FEMA P-58 analysis. However, ASCE 7-10 uses Risk-Targeted hazard values, capped by deterministic ground motions, to determine the design level of the building. The difference between Hazard and Risk-Targeted values, as well as the effect of deterministic capping of the design values, create fluctuations in losses for the various sites examined here. For example, the San Bernardino site is in a region where the deterministically capped ground shaking intensity is significantly lower than the 475 year event, so expected losses are relatively high compared to other sites.

Figure 3 shows the building closure times for this same set of 8-story steel moment frame buildings designed and located in various cities; Figure 3a is for the 475 year earthquake level (with closure times ranging from 7 to 10 months) and Figure 3b is the 2475 year earthquake level (with closure times ranging from 7 to 18 months). These figures show that, like repair cost, the Building Code does not limit downtime and the building performance varies from site to site.

These downtimes may appear excessive for code conforming buildings, however downtimes on the order of months to years have been broadly observed significant seismic events. In the recent 2011 Christchurch Earthquake, closure times of more than a year and a half were observed (Baker et al. 2016).

Summary of Code Conforming Buildings in California

This study shows the seismic performance expectation for an 8-story steel frame building designed and built in various cities throughout California. This same analysis has also been completed for a wide range of building types, though not shown here. The expected performance differs between building types, but the big-picture results are similar; new code-compliant buildings are expected to be closed for 6-12 months (or more for taller buildings) after a 475 year earthquake and up to 1.5+ years for a 2475 year earthquake (with a substantial chance of demolition). Repair costs are expected to be 5-25% for the 475 year earthquake and 10-80% for the 2475 year earthquake.

This demonstrates that the current approach to designing new buildings in California results in *safe but disposal buildings*.

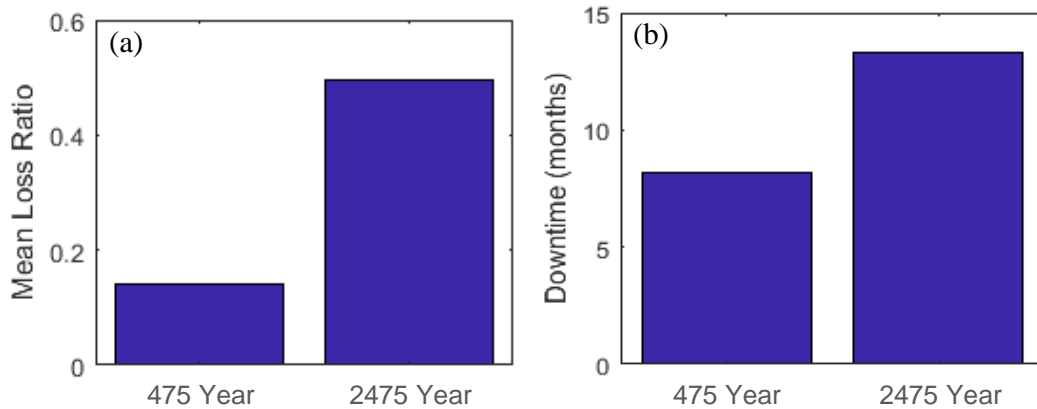


Figure 1. Expected performance for an 8-story steel frame building in Northridge CA.

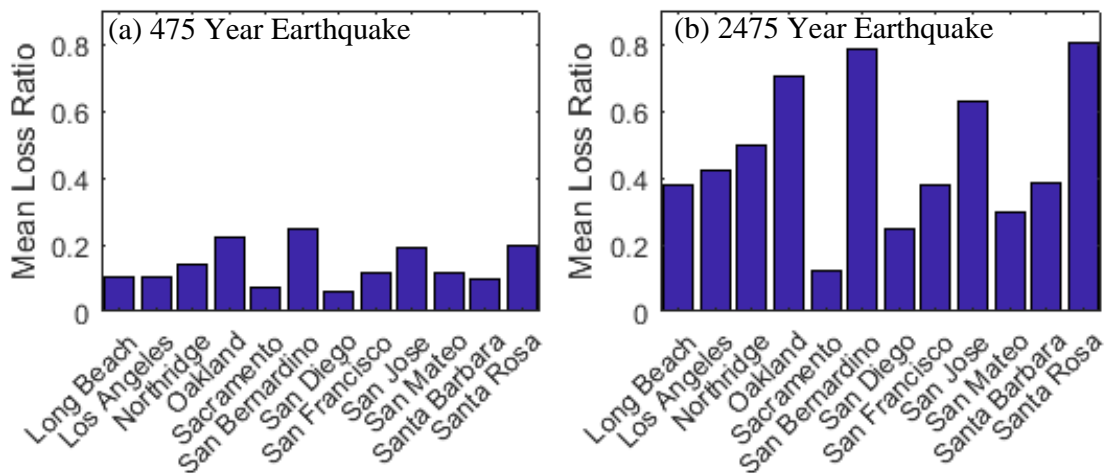


Figure 2. Expected repair costs for an 8-story steel frame office building in various California cities.

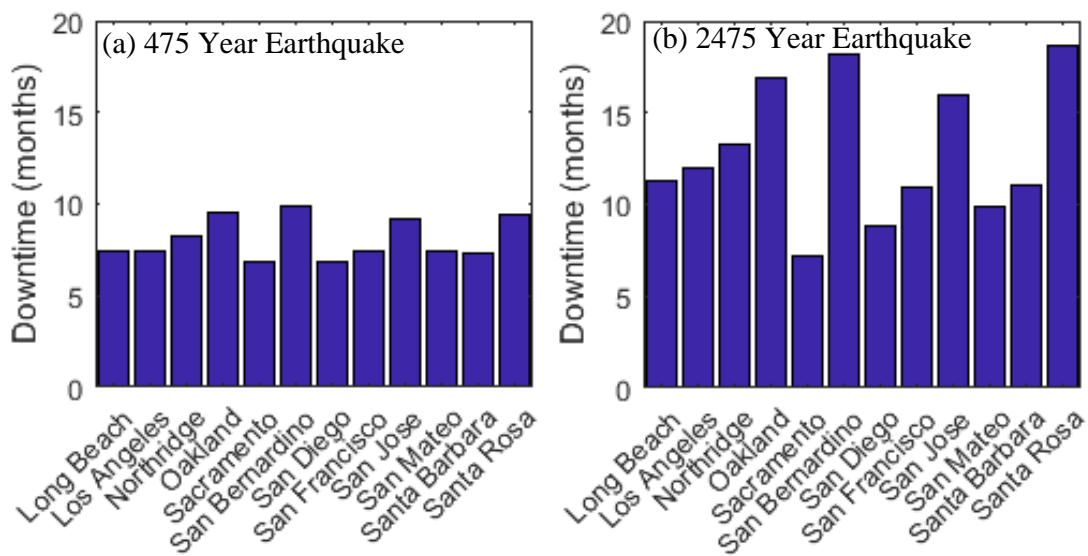


Figure 3. Expected closure times for an 8-story steel frame office building in various California cities.

Designing Beyond the Building Code

Enhanced Design

There is desire to build buildings better in California, such that buildings can be immediately occupied and used after an earthquake. A possible step toward this goal is to do “enhanced” design of buildings by designing them as critical facilities, as in Risk Category IV. When the example building in this study is designed as a critical facility (i.e. “enhanced” design), repair costs are considerably reduced, but the building closure times are still substantial. Therefore, this alternative design method creates a better building, but it does not achieve Immediate Occupancy performance. Long closure times, even for these “enhanced” designs, come from the fact that *there will still be damage that requires repair before the building can be occupied and used* (even though the damage is reduced). Furthermore, where repairs are required, there are also time consuming actions required before repairs may begin, i.e. impeding factors, which can delay repairs ~6 months after a large urban earthquake.

Even though this approach to designing a building as a critical facility clearly does not achieve Immediate Occupancy performance, it is possibly *the best quick fix* to get better performance in the interim, while more complete design rules are created for achieving Immediate Occupancy performance. It should be made clear that such an approach is an interim fix and has been shown to not achieve the fundamental goal of Immediate Occupancy.

Direct Resilient Design

The resilient design method involves making building-specific design and detailing decisions to minimize damage and repair time as described in Haselton et al. (2018). Examples of building-specific design/detailing decisions include: strengthening component anchorage to prevent failure, reducing shear stress in the gravity slab-column connections to limit their damage, and increasing the stiffness of specific lateral resistance lines to reduce the drifts and damage to certain portions of the building. Further action may be taken on the part of the building owner

to minimize impeding factors that must be handled ahead of design; these might include keeping an engineer on retainer to do a building inspection following a seismic event and keeping expected repair costs within the operating budget to avoid fundraising following a seismic event. A resilient design requires a specific performance goal and the cooperation of the design team to make all of the building systems interact for resilience.

Seismic Performance Expectations for Improved Design

This section looks at how the seismic performance can be improved by changing how California buildings are designed, looking at two possible approaches (a) making a simple modification to the Building Code such that all buildings are designed as critical facilities, hereafter referred to as the “enhanced” design method and (b) using a direct resilient-design approach that has been recently used for some buildings in California for building owners who desired better performance, hereafter referred to as the “resilient” design method.

Figures 4 and 5 show the results for buildings designed as critical facilities (i.e. the enhanced design approach). Figure 4 shows expected repair costs, and Figure 5 shows the expected building closure times. Repair costs are substantially reduced by this better design, but the building closure times are still substantial (though reduced some), and do not achieve an Immediate Occupancy performance goal.

Table 1 summarizes the results from Figures 4-5 for enhanced design buildings and compares them with the performance expected from recent resilient design projects in California, as described in Haselton et al. (2018). The comparisons show that the process of direct resilient design can deliver significantly better performance as compared with using a prescriptive requirement of designing a building as a critical facility. The resilient design approach substantially reduces building closure time and repair costs, and it can be used to achieve Immediate Occupancy performance.

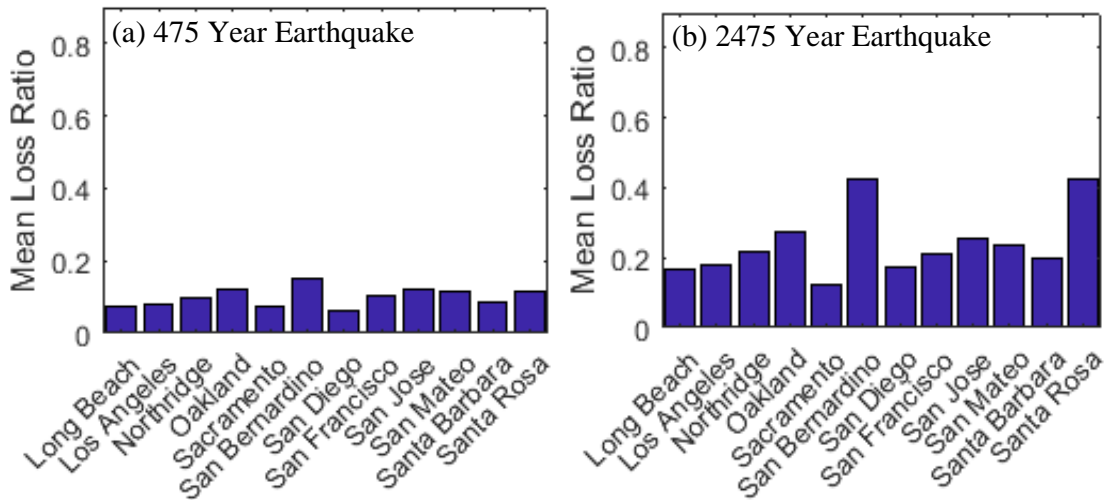


Figure 4. Expected repair costs for an 8-story steel frame enhanced design building in various California cities.

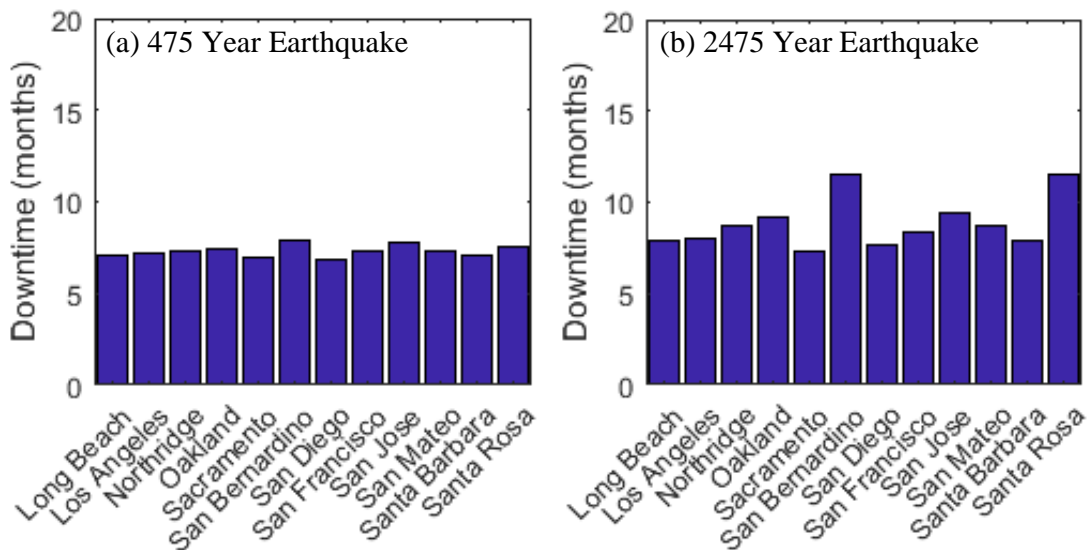


Figure 5. Expected building closure times for an 8-story steel frame enhanced design building in various California cities.

Table 1. Comparison of seismic performance between a standard code design, an enhanced code design method, and recent resilient-design projects.

Seismic Performance Metric	Design Approach	475 Year Earthquake	2475 Year Earthquake
Closure time	Code	7-10 months	7-24 months
	Enhanced	7-8 months	7-12 months
	Resilient	1-4 weeks	--
Repair Costs	Code	5-25%	10-80%
	Enhanced	5-15%	10-40%
	Resilient	~2%	--

These recent projects (where the owner elected for a resilient building) have also shown that direct resilient design is feasible in practice. Furthermore, the additional cost for resilient design to achieve near-Immediate-Occupancy performance is estimated to be approximately 1-3% of the building cost (Haselton, 2018). This direct resilient design process could also be used to inform future prescriptive Building Code design requirements to achieve Immediate Occupancy.

Conclusion

Until recently Structural Engineers, building departments, and the general public have accepted *safe but disposable buildings*, resulting in excessive repair cost and downtime. It is shown in this study that a 475 year seismic event in California could cause repair costs upwards of 20% of building value and functional recovery times near a year. The 2475 year event could cause repair costs high enough to warrant demolition and replacement of the building and functional recovery nearing 2 years.

Design buildings as critical, or Risk Category IV, is a possible first step toward resilient design. This prescriptive measure could reduce repair costs in the 2475 year event by half; however downtimes remain on the order of months.

Building-specific resilient design can be tailored to the specific function of the building and the needs of the building owner. In the case where the building must be occupiable immediately following a seismic event, recently designed buildings have shown this to be possible for a low cost (1-3% of the building value). This resilient design can be achieved by using the FEMA P-58 analysis method in the design process.

In the future, this study could be extended to create quantitative prescriptive Building Code design requirements to achieve Immediate Occupancy seismic performance.

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References

- ASCE, 2016, *Minimum Design Loads for Buildings and Other Structures*, ASCE Standard ASCE/SEI 7-16, American Society of Civil Engineers, Reston, VA.
- Baker J.W., Cremen G, Giovinazzi S, and Seville E, 2016, *Benchmarking FEMA P-58 performance*

predictions against observed earthquake data - A preliminary evaluation for the Canterbury earthquake sequence. New Zealand Society for Earthquake Engineering Conference, April 2016.

FEMA, 2012, *FEMA P-58-1: Seismic Performance Assessment of Buildings*, Applied Technology Council, Redwood City, CA.

Haselton, C.B., R.O. Hamburger, and J.W. Baker (2018). "Resilient Design and Risk Assessment using FEMA P-58 Analysis", *Structure Magazine*, March 2018.

Moehle J, Deierlein G., 2004, A Framework Methodology for Performance-Based Earthquake Engineering. *13th World Conference on Earthquake Engineering*, Vancouver, Canada.

REDi, 2013. *Resilience-based Earthquake Design Initiative for the Next Generation of Buildings*, Ibrahim Almufti and Michael Willford, Arup.

Seismic Performance Prediction Program (SP3), 2018. © Haselton Baker Risk Group, www.hbrisk.com.