

EVALUATING THE VARIABILITY IN FUNCTIONAL RECOVERY PERFORMANCE OF MODERN BUILDINGS ACROSS THE UNITED STATES

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Abstract: *As building codes in the United States move toward the development of functional recovery provisions aimed at reducing recovery times following earthquakes, it is critical to benchmark how buildings designed following life-safety provisions perform in terms of new recovery-based performance metrics. In this study, the functional recovery performance of an 8-story reinforced concrete shear wall archetype, designed following current life-safety provisions, is evaluated in 34 cities across the United States. A risk assessment is conducted for functional recovery time, using functional recovery target times ranging from two weeks to two years. Two functional recovery proxies are also considered, one for nonstructural damage (i.e., damage to partitions) and one for safety-critical structural damage (i.e., red tags). The results are disaggregated by spectral acceleration to identify drivers of recovery risk. Results show that the risk of exceeding short recovery targets (i.e., recovery targets ranging from two weeks to one year) varies considerably across the 34 cities evaluated with current risk-targeting methods for collapse risk. The risk of exceeding long recovery targets (i.e., greater than one year) as well as the risk of incurring red tags, however, is more uniform for sites with high seismicity, with the exception of deterministically capped sites. Overall, this study highlights the need to consider design interventions to maximize the likelihood of achieving short recovery times and reduce the variability in functional recovery risk.*

1. Introduction

Current seismic design provisions in the United States aim to ensure certain life-safety performance objectives, but do not provide direction to target specific levels of post-earthquake function (ASCE/SEI, 2022). Recent studies have shown that buildings designed following these minimum standards may not perform well when evaluated against resilience-based performance metrics. Estimates of functional recovery time by Molina Hutt et al. (2022a), Cook et al. (2023), and Terzic and Kolozvari (2022) all have shown that modern reinforced concrete shear wall (RCSW) buildings may take from approximately seven months to over a year to reach a functional recovery state following a design level earthquake. Blowes et al. (2023) also performed a risk-based analysis of modern RCSW buildings in Seattle, WA and found an approximately 40 % probability of the functional recovery time exceeding 4 months over 50 years. In an effort to develop clear functional recovery objectives and parallel design requirements to improve recovery performance, the Building Seismic Safety Council (BSSC) in the United States is advancing the NEHRP (National Earthquake Hazard Reductions Program) provisions to include new prescriptive recovery-based design requirements (BSSC, 2023).

While the goal to develop recovery-based design provisions has only recently been identified, meaningful work has already been conducted in this research area. Work to date has focused on developing functional recovery time estimation frameworks, such as the REDI framework (Almufti and Willford, 2013), the F-REC framework (Terzic et al., 2021), the TREADS framework (Molina Hutt et al., 2022b), and the Cook et al. (2022)

methodology that has been adopted by the ATC-138 Project (Applied Technology Council, 2021). Significant efforts have also been put into collecting data on impeding factor delays (e.g., Paul et al., 2018) and repair sequencing (e.g., Terzic et al., 2016), as well as benchmarking the probability of unsafe placards against past events (Cook et al., 2021). Studies using these frameworks have primarily focused on reinforced concrete shear wall buildings (Cook et al., 2023; Molina Hutt et al., 2022b, 2022a; Terzic and Kolozvari, 2022). Researchers have also used this new generation of functional recovery time estimation frameworks to consider existing buildings, other types of modern construction, or the impact of design interventions (Galvis, 2022; Issa et al., 2023; Mohammadgholibeyki et al., 2023; Vahanvaty, 2021). Most of these studies have focused on performance at the design-level earthquake (DBE), but a few have considered performance across a range of hazard levels. Blowes et al. (2023) performed a risk-based analysis for functional recovery performance of modern RCSW buildings. Vahanvaty (2021) and Cook et al. (2023) also considered the impact of design interventions to improve recovery at intensities ranging from a 100- to a 4975-year return period for reinforced concrete buildings. Furthermore, to develop a national standard in the U.S., more effort is needed to benchmark current recovery performance that is expected across a wider range of geographic locations. More extensive studies of different construction types are also needed.

Building codes in the United States use risk-targeting to ensure a similar collapse risk given the variance in seismic hazard across the United States. Risk-targeting was first implemented in the 2009 NEHRP design provisions (FEMA, 2009) using the methodology outlined by Luco et al. (2007). Horspool et al. (2023) recently implemented the methodology by Luco et al. (2007) to develop a national seismic risk model for collapse risk in New Zealand. Hulseley et al., (2022) advanced the notion of risk-targeting to consider a serviceability limit state with the goal of ensuring a uniform risk of losing serviceability. Hulseley et al., (2022) also propose using damage to partitions as a proxy for loss of serviceability. To support the development of the 2026 NEHRP design provisions, the BSSC is currently working to develop a framework for risk-targeting for functional recovery performance objectives. Like the work by Hulseley et al. (2022), this effort targets a uniform risk of exceeding a given resilience-based criteria, specifically, the risk of exceeding various recovery time targets.

In support of the BSSC's work to develop the new NEHRP provisions, this study aims to quantify the functional recovery performance across 34 U.S. cities for buildings designed for current life-safety provisions using risk-based metrics (e.g., 50-year probability of the functional recovery time exceeding 4 months). This study also aims to compare the functional recovery risk across the 34 U.S. cities. To do so, we consider an 8-story RCSW archetype building designed following modern life-safety design provisions for the relevant seismicity across the 34 cities. The functional recovery time of each archetype building is simulated using the Cook et al. (2022) methodology at return periods ranging from 43 to 4975 years. A risk-based assessment is then performed to benchmark the risk of exceeding various functional recovery targets ranging from two weeks to two years. For an example site in Los Angeles, CA, the results are then disaggregated by spectral acceleration to show which return periods drive the risk of exceeding different recovery targets. In addition, a risk-based assessment is conducted for one proxy for nonstructural damage (i.e., partition wall damage) and one proxy for structural damage that hinders tenant safety (i.e., red tags). By using these proxies, we can evaluate trends in the occurrence of nonstructural and structural damage across intensity levels and across the 34 sites. Further, the proxies are used to identify the return periods that drive the risk of incurring each type of damage. Overall, this study adds to the existing body of work on functional recovery by calculating the 50-year risk of exceeding a wide range of functional recovery targets and provides insight into the current variability of recovery risk that exists across the United States.

2. Archetype Building

The archetype considered in this study is an 8-story residential special reinforced concrete shear wall building. Using the Seismic Performance Prediction Program (SP3) (Haselton Baker Risk Group, 2023), an archetype representative of typical design was generated to meet minimum design requirements outlined in ASCE 7-16 (ASCE/SEI, 2016) for Risk Category II (i.e., with an importance factor of 1.0) and site class D. The archetype building was regenerated to meet the minimum seismic design requirements of ASCE/SEI 7 in each of the 34 cities, representing a theoretical new building design in city, rather than the condition of existing buildings. These 34 cities were originally studied in the development of the 2009 NEHRP Provisions (FEMA, 2009) and more recently by Luco et al. (2017) for collapse risk, as well as in the 2020 NEHRP Provisions (FEMA, 2020). The sites selected are in cities with high seismicity or with a high population. Structural and nonstructural

components in the archetype building were auto-populated using SP3 for a typical residential occupancy and for the seismic design category of the archetype. To benchmark current practice, nonstructural components were selected to represent typical construction, with no additional improvements targeting rapid recovery.

The structural response of the archetype was determined using the SP3 Structural Response Prediction Engine (Haselton Baker Risk Group, 2023). Using this tool, ground motions were selected and scaled to eight intensity levels ranging from 43- to 4975-year return periods. The engineering demand parameters (EDPs) output from the Structural Response Prediction Engine were sampled to estimate damage using the FEMA P-58 methodology (FEMA, 2018), as implemented in SP3. Damage to components was then used to determine the functional recovery time using the Cook *et al.* (2022) methodology. Default impeding factor delays outlined in the Cook *et al.* (2022) methodology were sampled to determine the functional recovery time estimates at each of the eight intensity levels considered. In addition to functional recovery times, damage to partitions that impedes function (DS3 or worse) was determined from the FEMA P-58 analysis and the red tag probability was calculated at each intensity level using fault trees outlined in Cook *et al.* (2021), as implemented by Cook *et al.* (2022). The result of the functional recovery assessment of the archetype is a suite of simulated functional recovery times and/or damage state for each hazard level and site considered. The results are simulated using a Monte Carlo process, considering record-to-record ground motion uncertainty; material, modelling, and quality of construction uncertainty; uncertainty in structural response; component damage uncertainty; and impeding time uncertainty.

3. Methodology

To determine the functional recovery risk across the 34 cities considered, we adopt methods presented in Blowes *et al.* (2023) to calculate the 50-year risk of exceeding each recovery target. In this work, traditional methods to calculate collapse risk (Cornell, 1968) are adapted to consider the probability of failure as the probability of the functional recovery time exceeding a pre-defined recovery target. In this study, we consider six recovery targets ranging from two weeks to two years. The targets selected are intended only to benchmark recovery performance that is achievable with current design provisions and do not represent the functional recovery time objectives in future NEHRP provisions.

The risk-based assessment is performed by integrating the hazard curve, $\lambda_{IM}(IM)$, at each of the 34 sites with a functional recovery time fragility that provides the probability of exceeding a recovery time target as a function of spectral acceleration, $P(T_{FR} > T_{Target} | IM)$. The annual risk of the functional recovery exceeding a functional recovery target, $\lambda_{T_{FR} > T_{Target}}$, is outlined in Equation 1.

$$\lambda_{T_{FR} > T_{Target}} = \int_0^{\infty} P(T_{FR} > T_{Target} | IM) |d\lambda_{IM}(IM)| \quad (1)$$

The functional recovery time fragilities were developed for each site and recovery target by fitting a lognormal CDF to the simulated recovery time outcomes. The Probit link function was used to fit the fragility functions, using scripts developed by Baker (2015). Finally, the 50-year risk of exceeding each recovery target was calculated to compare the uniformity of risk across the sites when current risk-targeting methods are used.

In addition to functional recovery time, we follow a similar process for two additional parameters. First, we evaluate the probability of exceeding the third damage state (DS3) for partitions anywhere in the building to provide a proxy for nonstructural component damage that impedes function. Second, we consider red-tag probability as a proxy for safety-critical structural damage. Safety-critical damage must be addressed, through temporary or full repair, before the structure can be occupied. To evaluate the risk of incurring partition damage or red tags, we followed the same procedure by developing partition damage and red tag fragilities. Each fragility was integrated with the hazard curve at each site to find the 50-year partition damage and red tag risk. Disaggregation by spectral acceleration was also performed to identify the return period of the ground motion that has the largest contribution to the risk of each consequence (i.e., exceeding different recovery targets, incurring partition damage or red tags).

4. Functional Recovery Risk Assessment

The fragility functions seen in Figure 1a describe the probability of exceeding each target recovery time as a function of spectral acceleration, as well as the hazard curve at the Los Angeles, CA, site (34.05, -118.25), which are integrated to calculate the 50-year risk of exceeding each recovery target. Employing the same

methodology, the 50-year probability of the functional recovery time exceeding each recovery target for the 34 cities is summarized in Table 1. Results align with work recently presented by Blowes et al. (2023) that considered the functional recovery risk for a suite of reinforced concrete shear wall buildings located in Seattle, WA. Using a different functional recovery estimation method developed by Molina Hutt et al. (2022b), the study showed a probability of exceeding four months and one year of approximately 40 % and 8 % respectively for a similar 8-story RCSW archetype. From Table 1, we see results for the Seattle site in this study are similar, with a 41 % probability of the functional recovery time exceeding four months and an 11 % probability of exceeding one year. Results of both studies highlight that the risk of exceeding short recovery targets is high when minimum design provisions are used.

Comparing across cities, we see that the risk of exceeding short recovery targets also varies considerably. Even within close geographic areas, there can be considerable variability with current risk-targeting methods for collapse. For example, the site selected in San Francisco has a 57 % probability in 50 years of the functional recovery time exceeding four months. In nearby Oakland, the risk is approximately 73 %. By contrast, the risk of exceeding long recovery targets is more uniform. For example, the 50-year risk of exceeding the recovery target of 1 ½ years range from under 1 % for sites with low seismicity to approximately 3 %, with notable exceptions for sites that are deterministically capped (e.g., Oakland and San Jose). The risk may be more uniform for long recoveries because the types of damage that drive long recoveries are more similar to those that cause collapse.

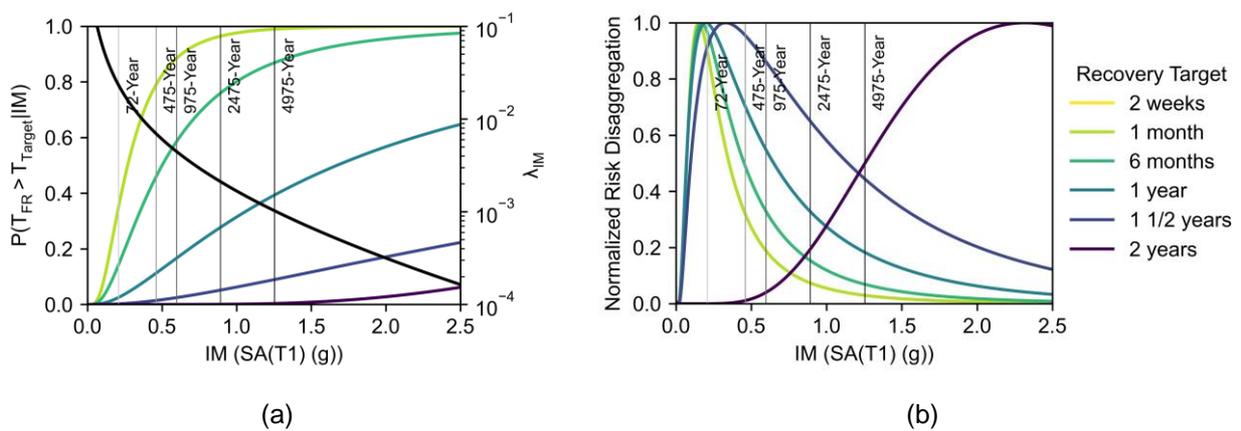


Figure 1. (a) Hazard curve and fragility functions for the probability of exceeding various functional recovery time targets as a function of the spectral acceleration at the first mode period (SA(T1)) and (b) disaggregation by SA(T1) of the risk of exceeding functional recovery time (T_{FR}) targets for a residential 8-story RCSW archetype building in Los Angeles, CA.

Figure 1b provides the disaggregation by spectral acceleration of the risk of exceeding each functional recovery target for the Los Angeles site. The plot is normalized to help identify the return periods that drive the risk of exceeding each target. The disaggregation exercise illustrates that the risk of exceeding short recovery targets is governed by frequent earthquakes (i.e., 72-year return period). More generally, for recovery targets less than the building replacement time (583 days), earthquakes with return periods under 475 years govern the risk. The risk of exceeding longer recovery targets is governed by increasingly rare events where buildings have a much higher likelihood of incurring irreparable damage. These results also suggest that preventing the types of damage incurred in frequent earthquakes would also be very effective in reducing the high risk of exceeding the short recovery targets (i.e., results for the two-week to six-month targets in Table 1). These results are similar to trends found by Blowes et al. (2023). Further work is needed, however, to perform the same disaggregation exercise across the 34 cities and investigate the variability in these trends.

Table 1. 50-year probability of exceeding various recovery targets across the 34 sites considered.

City	50-Year Probability of Exceeding Recovery Target						
	2 weeks	1 month	4 months	6 months	1 year	1 ½ years	2 years
Los Angeles	66%	66%	55%	43%	14%	2.1%	0.1%
Century City	72%	72%	62%	51%	17%	2.6%	0.1%
Northridge	82%	82%	73%	61%	22%	3.6%	0.1%
Long Beach	69%	69%	57%	45%	14%	2.1%	0.1%
Irvine	61%	61%	48%	37%	11%	1.6%	0.1%
Riverside	82%	82%	74%	63%	24%	3.6%	0.1%
San Bernardino	85%	85%	77%	67%	24%	3.9%	0.1%
San Luis Obispo	36%	36%	28%	21%	6%	0.7%	~0%
San Diego	39%	39%	31%	24%	7%	1.1%	0.1%
Santa Barbara	42%	42%	32%	24%	7%	1.3%	0.1%
Ventura	52%	52%	40%	30%	9%	1.5%	0.1%
Oakland	81%	81%	73%	62%	24%	4.1%	0.3%
Concord	73%	73%	59%	47%	17%	3.5%	0.3%
Monterey	53%	53%	41%	31%	9%	1.2%	~0%
Sacramento	76%	76%	66%	56%	19%	2.5%	~0%
San Francisco	68%	68%	57%	46%	16%	2.9%	0.2%
San Mateo	77%	77%	66%	52%	17%	2.6%	0.1%
San Jose	89%	89%	82%	72%	29%	5.2%	0.4%
Santa Cruz	73%	73%	61%	48%	16%	2.8%	0.2%
Vallejo	74%	74%	62%	51%	19%	4.0%	0.4%
Santa Rosa	68%	68%	57%	46%	16%	2.7%	0.1%
Seattle	51%	51%	41%	33%	11%	2.0%	0.2%
Tacoma	59%	59%	50%	41%	14%	2.4%	0.2%
Everett	51%	51%	42%	33%	11%	1.6%	0.1%
Portland	37%	37%	29%	23%	7%	1.0%	~0%
Salt Lake City	17%	17%	14%	12%	5%	0.9%	0.1%
Boise	12%	12%	7%	5%	1%	0.1%	~0%
Reno	54%	54%	43%	33%	11%	1.7%	0.1%
Las Vegas	31%	31%	24%	19%	6%	0.6%	~0%
St. Louis	11%	11%	9%	7%	2%	0.3%	~0%
Memphis	14%	14%	12%	10%	4%	0.8%	0.1%
Charleston	18%	18%	16%	15%	7%	1.6%	0.2%
Chicago	2%	2%	1%	1%	~0%	~0%	~0%
New York	7%	7%	5%	3%	1%	~0%	~0%

5. Risk Assessment of Nonstructural and Safety-Critical Structural Damage

The risk of incurring partition damage that impedes function (DS3 or worse in FEMA P-58), which is used here as a proxy for severe nonstructural damage, ranges from under 1 % to 28 %, varying considerably across the

34 cities surveyed, as summarized in Table 2. The disaggregation of the risk of partition damage by spectral acceleration for the Los Angeles site, shown in Figure 2b, indicates that the risk is driven by earthquakes, with return periods around 2475-years. The risk of incurring damage to partitions alone is lower than the risk of exceeding short recovery targets. This trend is observed because when the functional recovery time is considered, the reliability of the entire system of components is evaluated. The recovery time risk therefore relies on the performance of many components, some of which may have a higher likelihood of impeding function than partitions. This finding also indicates that to achieve a given functional recovery reliability target, higher individual component reliabilities may be necessary.

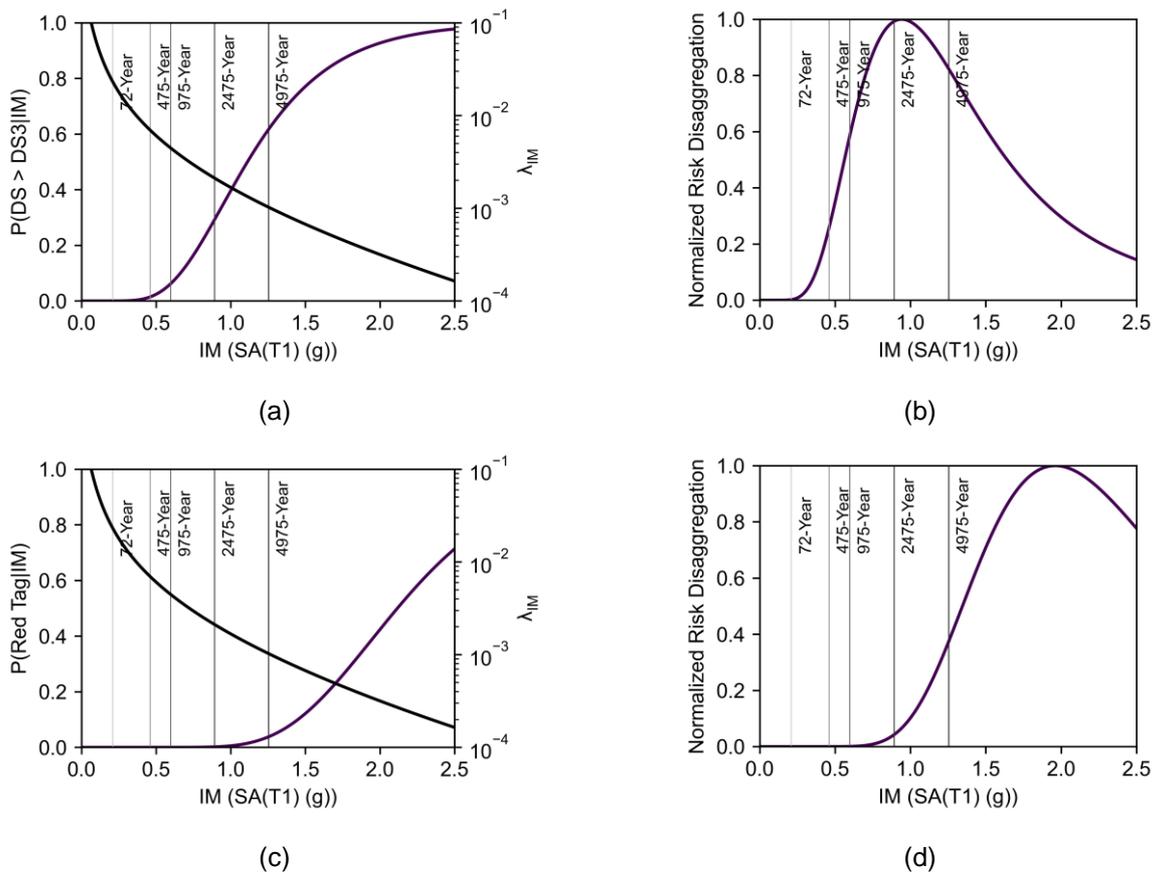


Figure 2. (a) Hazard curve and fragility functions for the probability of incurring damage to partitions as a function of the spectral acceleration at the first mode period (SA(T1)) and (b) disaggregation by SA(T1)) of the risk of red tags. (c) Hazard curve and fragility functions for the probability of incurring structural red tags as a function of the spectral acceleration at the first mode period (SA(T1)) and (d) disaggregation by SA(T1)) of the risk of red tags.

Finally, we consider the risk of incurring severe structural damage by studying the 50-year risk of red tags as a proxy for structural damage that poses a safety risk to tenants. Figure 2c shows the fragility developed to represent the probability of red tags as a function of spectral acceleration of the first mode period. From Table 2, the 50-year risk of incurring red tags is low, ranging from under 1 % to approximately 3 % across the 34 sites considered. There are notable exceptions where the 50-year red-tag probability exceeds 5 %, which are primarily near-fault, deterministically capped, sites (e.g., San Bernardino, Concord, San Jose). While a red tag does not indicate that a building will be irreparable, it does indicate more extensive structural damage and the triggering of lengthy impeding factor delays which increases functional recovery times. The disaggregation of the example site in Los Angeles, shown in Figure 2d, indicates that the risk of red tags is governed by extremely rare earthquakes with return periods greater than 4975 years. Further work is required to study the return periods and spectral acceleration thresholds that govern the red tag risk across all 34 sites.

Table 2. 50-year probability of incurring damage to partitions and red tags across the 34 sites considered.

City	50-Year Probability of Partition Damage (DS ≥ DS3)	50-Year Probability of Red Tag
Los Angeles	7.6%	0.9%
Century City	9.3%	1.4%
Northridge	15%	2.3%
Long Beach	8.9%	1.1%
Irvine	8.4%	0.8%
Riverside	10%	0.9%
San Bernardino	24%	5.5%
San Luis Obispo	0.9%	~0%
San Diego	3.3%	0.2%
Santa Barbara	6.2%	1.0%
Ventura	6.2%	0.8%
Oakland	16%	3.3%
Concord	24%	5.6%
Monterey	1.5%	~0%
Sacramento	4.9%	0.1%
San Francisco	9.2%	1.1%
San Mateo	20%	3.7%
San Jose	28%	5.5%
Santa Cruz	15%	2.7%
Vallejo	22%	4.8%
Santa Rosa	11%	2.4%
Seattle	3.6%	0.2%
Tacoma	4.0%	0.2%
Everett	3.2%	0.2%
Portland	3.8%	0.3%
Salt Lake City	1.0%	~0%
Boise	0.9%	~0%
Reno	5.3%	0.6%
Las Vegas	1.1%	~0%
St. Louis	0.1%	~0%
Memphis	0.7%	~0%
Charleston	0.6%	~0%
Chicago	~0%	~0%
New York	~0%	~0%

6. Conclusions

In this study, a risk-based assessment was performed to evaluate the 50-year probability of the functional recovery time exceeding targets ranging from two-weeks to two years for 34 cities across the United States. Findings from this study indicate that the 50-year risk of exceeding short recovery targets is both high and nonuniform across the 34 cities analyzed. The 50-year risk of the functional recovery time exceeding one year is low and varies considerably less, with the exception of near-fault sites. For the two proxies considered (i.e., partitions as a proxy for nonstructural damage and red tags as a proxy for safety-critical structural damage),

we see again that the risk of incurring damage to partitions and red tags also varies considerably between sites.

The results were disaggregated by spectral acceleration for a site in Los Angeles, CA to show an example of the return period that drives risk for a site with high seismicity. For the Los Angeles site, the risk of exceeding short recovery targets is dominated by frequent earthquakes and the risk of exceeding long recovery targets is dominated by rarer events, which is in alignment with results from Blowes *et al.* (2023) for a different archetype, framework, and site. The disaggregation exercise also highlighted that the risk of damage to partitions, our proxy for nonstructural damage, is dominated by the 2475-year hazard level. By contrast, the risk of red tags is driven by very rare earthquakes (*i.e.*, greater than 4975 years). Further work is needed, however, to comment on the variability in the drivers of risk across sites. Work is also needed to study the drivers of risk at deterministically capped sites and at sites with significantly lower seismicity that may incur nonstructural damage only in very rare earthquakes.

This study ultimately illustrates two key findings. First, designing buildings using current life-safety design provisions does not ensure a low risk of exceeding functional recovery targets ranging from two weeks to one year. Second, current risk-targeting methods for collapse risk do not ensure uniform risk for functional recovery when buildings are designed for life-safety provisions. Overall, these findings highlight the importance of ongoing BSSC efforts to develop recovery-based design provisions and perform risk-targeting for recovery.

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