# Risk Targets for Recovery-Based Design of Individual Buildings Considering Regional Performance

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ABSTRACT: The development of risk-targeted design loads for recovery-based design first requires consensus around acceptable levels of building risk, specifically in terms of recovery-based performance objectives such as reoccupancy and functional recovery. This study provides context to potential risk-based building recovery performance objectives by quantifying the relationship between target building-level recovery performance and regional recovery using a probabilistic regional seismic loss analysis of residential buildings in downtown San Francisco. In comparing building risk with regional risk, we find that the risk of failing regional recovery objectives was significantly higher than comparable levels of individual building risk.

In the U.S., the concept of functional recovery has emerged as a mechanism to improve community resilience by developing recovery-based design principles for buildings. The fundamental goal of functional recovery is to limit downtime in individual buildings, thereby expediting the recovery of communities after natural hazard events (NIST & FEMA, 2021). Indeed, ongoing efforts are currently underway to identify recovery-based prescriptive seismic design provisions for use in future U.S. building codes (FEMA, 2020). A key first step in this development is to (a) identify the buildings and community services that require rapid recovery to mitigate long-term community consequences, and (b) identify minimum seismic design loads (ground motions) required to ensure acceptable performance.

Risk-targeted ground motions (Luco et al., 2007) offer an attractive approach to directly account for regional variation in hazard while simultaneously providing a consistent relationship between risk-based and ground motion conditional performance across the nation. In 2012, a NIST report (NIST, 2012) proposed that future codes generate risk-targeted ground motions for alternative building performance objectives such as functional recovery. As a starting point for future code development, the report suggests that a future performance target for the recovery of buildings may be something like a 10 % probability of unacceptably long recovery in 50 years, but more detailed analysis of acceptable risk is needed.

At the community level, many cities, researchers, and resilience advocates have developed region-specific resilience plans to identify the critical hazards faced by their communities and propose community-specific recovery and mitigation goals (e.g., OSSPAC, 2013; SPUR, 2012). While the specific recovery goals differ, each resilience plan identifies various community services that are critical for community recovery and assigns a recovery timeline goal to mitigate long-term community consequences. For example, based on a 5 % vacancy rate, the San Francisco Planning and Urban Research (SPUR) resilience plan states that 95 % of residential housing in San Francisco should achieve shelter-in-place capacity within 24 hours to prevent significant outmigration of residents after a future large earthquake, roughly corresponding to a 10 % chance of being exceeded in 50 years (SPUR, 2012).

The acceptable level of regional risk implied by the SPUR resilience plan seems to confirm the 10 % in 50 years risk target for the recovery-based design of new buildings suggested by the NIST report. However, these two metrics differ in one distinct regard: one defines the performance for an individual building or asset, and the other defines the performance for a collection of buildings of infrastructure assets.

Therefore, to inform future code development for recovery-based design, we use this study to ask a simple question: are these two metrics the same? In other words, will designing individual buildings to meet building-level, recovery-based, risk goals using risk-targeted ground motions achieve similar levels of community-level risk?

In this study, we explore the relationship between building-level risk targets and the overall building-stock risk using probabilistic regional seismic loss analysis (e.g., DeBock & Liel, 2015) to account for spatial variation of ground motion intensity for any given earthquake rupture scenario. To compare building-level performance objectives and regional recovery, we quantify the regional performance, in terms of overall post-earthquake shelter-in-place capacity, of a set of residential buildings in downtown San Francisco for various building-level performance objectives that could be set in future recovery-based standards. Using this method allows us to directly compare individual building risk with regional risk and explore the various features on which the relationship depends. From this comparison, we isolate the building-level risk targets required to achieve the residential community performance targets defined in the SPUR resilience plan.

## 1. STUDY REGION

To study the relationship between building-level performance objectives and regional performance, we use the building inventory data collected by Hulsey et al. (2022), as shown in Figure 1. The building inventory is comprised of 1,078 buildings in downtown San Francisco, consisting of various occupancies, structural systems, heights, ages, and architectural configurations. The building inventory was collected using tax assessor, land use, and LIDAR data from San Francisco's open-source portal (dataSD.org). However, among these characteristics, only the number and location of buildings within a given occupancy are critical for this study. Since the goal of this study is to quantify regional performance given building-level performance targets, we idealize the reoccupancy performance of each building based on the potential design objectives, instead of quantifying the performance of an existing set of buildings.


*Figure 1 - Map of the residential buildings assessed within the study region of downtown San Francisco.*

The regional performance objective in this study is interpreted from the SPUR resilience plan as less than a 10 % probability that over 5 % of the residential building stock will be unoccupiable

24 hours after an earthquake, over a 50-year timeframe (based on the statement that the magnitude 7.2 scenario earthquake roughly correlates to ground motions with a 10 % probability of exceedance in 50 years). Among the downtown inventory, 285 are classified as residential use. Therefore, to study the performance of the residential building stock, we only use the 285 residential buildings out of the full 1,078 in the dataset in our probabilistic regional seismic analysis.

## 2. IDEALIZED BUILDING PERFORMANCE

As previously stated, the goal of this study is to quantify regional performance given potential building-level performance objectives for new buildings, rather than quantifying the regional performance for an existing inventory. Therefore, in the regional assessment, the recovery performance of each building within the study region must be idealized and anchored to a proposed building-level design objective.

Similar to safety-based performance objectives, individual building performance is characterized by a fragility curve with a lognormal distribution; the fragility defines the probability of exceeding the target performance given ground shaking intensity (typically in terms of spectral acceleration) and the lognormal dispersion (β) is characterized by the uncertainty in ground motion, structural response, damage, and recovery, given ground shaking intensity. Here, we define the building-level recovery objective as reoccupancy within 24 hours of the earthquake, thus matching the proposed recovery objective from the SPUR report.

Once we establish the reoccupancy target, the recovery fragility shape, or dispersion, can be estimated. For safety-based performance objectives, the lognormal dispersion of the fragility is typically assumed to be 0.6 (FEMA, 2009). To determine the typical recovery-based dispersion, we assess the reoccupancy time of each building in the inventory using the performance-based recovery assessment method from Cook et al. (2022) and the SP3 software package (Haselton Baker Risk Group, 2023). We simulate reoccupancy times across a suite of ground motion intensities using the default structural response and component population algorithms from the software; lognormal fragilities are fit to each model's reoccupancy outcomes using maximum likelihood estimation (e.g., Baker, 2015). From this assessment, we determine that the lognormal dispersion for a 24-hour reoccupancy fragility is about 0.43 +/- 0.09, as shown in Figure 2. For the initial assessment, we select a dispersion of 0.5 to characterize the general shape of the 24-hour reoccupancy fragility; later in this study, we show the impact of this assumption on regional outcomes.

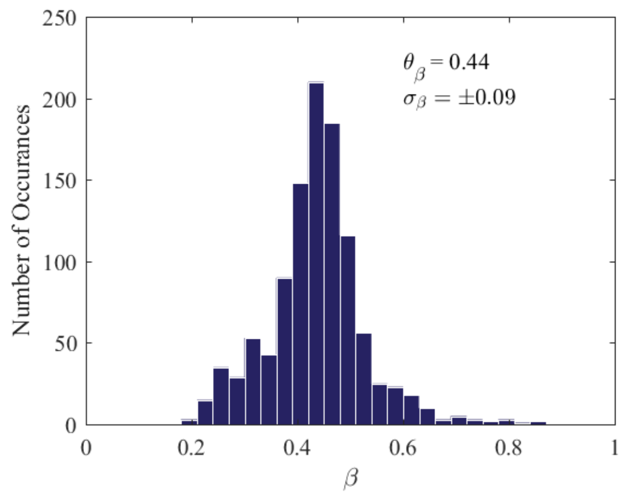


*Figure 2 - Lognormal dispersions (β) of fitted 24-hour reoccupancy fragilities for all 1,078 buildings in the study region.*

Given the assumed fragility shape, we illustrate the idealized target recovery performance for new buildings in Figure 3—the previously described assessment of the study region that uses the SP3 software only informs the assumed lognormal dispersion; the fragility in Figure 3 is intended to represent idealized performance of new buildings meeting recovery-based targets. Here, the spectral accelerations are normalized by the risk-targeted ground motion spectral accelerations ($Sa_{RTGM}$), which are calculated for each location within the region using the assumed lognormal dispersion of 0.5. Following life safety provisions, building reoccupancy is assumed to have a 10 % probability of exceedance given $Sa_{RTGM}$. Using the risk-targeted ground motions allows the proposed design loads for each building in the region to vary with hazard while maintaining equivalent building-level risk across the study region.

To explore the relationship between building risk and regional risk, risk-targeted ground motions are calculated for each building in the study region for various building-level risk targets, ranging from 1 % to 50 % probability of exceedance in 50 years, and the regional performance is quantified at each of these various building-level risk targets.

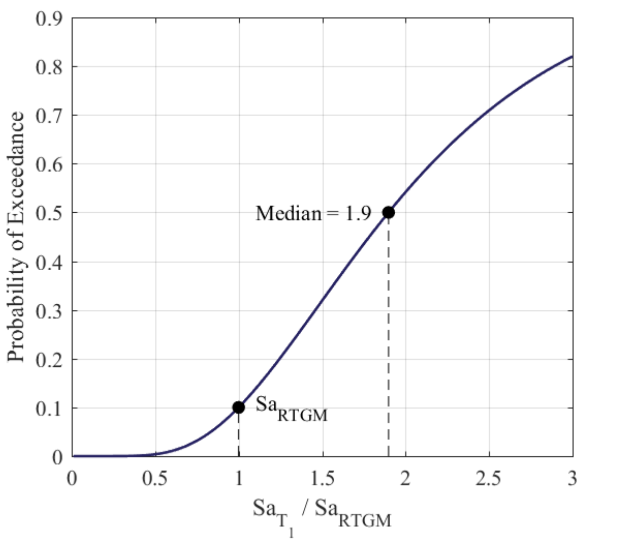


*Figure 3 - Idealized building 24-hour reoccupancy fragility for all buildings in the region, assuming a lognormal dispersion of 0.5.*

## 3. PROBABILISTIC REGIONAL SEISMIC ANALYSIS

To assess the regional performance of the 285 residential buildings, we compute the probability of exceeding the building-level recovery objective, as defined by the idealized building fragility, for each building using regionally distributed ground motion shake maps. The shake maps are spatially correlated and simulated across a suite of likely rupture scenarios (e.g., DeBock & Liel, 2015).

We characterize the regional seismicity using the UCERF2 rupture forecast model (USGS, 2008) considering faults within 200 km of the region to obtain a suite of 2,430 rupture scenarios; magnitudes (Mw) range from 5.5 to 8.5, as shown in Figure 4. We use a weighted average of the ground motion prediction equations defined in Abrahamson et al. (2014), Campbell & Bozorgnia (2014), and Chiou & Youngs (2014) to determine the expected value and dispersion of shaking intensity at each site. The dispersion of the predicted spectral accelerations are divided into two components: inter-event (i.e., variability between different events) and intra-event dispersion (i.e., variability from site-to-site within an event).

For each rupture scenario, we simulate spatially correlated ground shaking maps from the lognormal probability distributions of spectral acceleration at each site. Spatial correlation of the intra-event variability is simulated with the model developed by Loth & Baker (2013), which considers site-to-site distance and building period. Period-to-period correlation of the inter-event variability is simulated with the relationship developed by Baker & Jayaram (2008). The result of the analysis is 2,430 probabilistically simulated shake maps that capture uncertainty in ground shaking intensity at each site while maintaining spatial correlation. Each shake map is associated with a specific rupture scenario and recurrence rate, thus facilitating the calculation of regional risk.

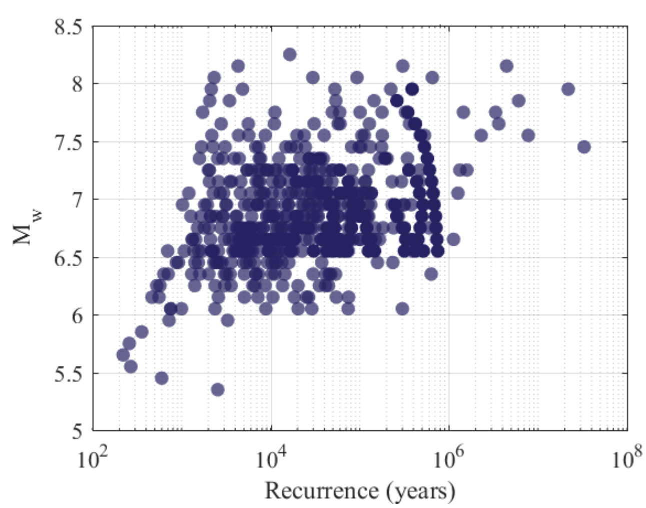


*Figure 4 - Magnitude ($M_w$) vs recurrence rate for each of the 2,430 earthquake rupture scenarios considered in this study*

We calculate the recovery performance of the region by summing all buildings that have reoccupancy times greater than 24 hours within a given earthquake rupture scenario and comparing the number of failed residential buildings with the community threshold for acceptable loss of building occupancy throughout the region (e.g., 5 % according to the SPUR report; here on referred to as the "community threshold"). Regional risk, in terms of frequency of exceedance, is calculated as the summation of the scenario recurrence rate times the probability that each scenarios exceeds the community threshold, as shown in Eq. (1); the annual frequency of exceedance can then be transformed into a 50-year probability of exceedance, assuming a binomial distribution as shown in Eq. (2). Note, when calculating the probability of exceeding the community threshold, the capacity of each building in the inventory is assumed to be independent, given the idealized fragility.

$$AFE = \sum_{i=1}^{n} (p_i * r_i) \qquad (1)$$

Where:

AFE = Annual frequency of exceeding the community threshold for acceptable building performance.

n = Number of rupture scenarios.

$r_i$ = Annual recurrence rate of each rupture scenario.

$p_i$ = Probability of exceeding the community threshold for a given rupture scenario.

$$R = 1 - e^{-50*AFE} \qquad (2)$$

Where:

R = The 50-year regional risk of exceeding acceptable performance.

AFE = Annual frequency of exceeding the community threshold for acceptable building performance from Eq. (1).

We verified the regional risk calculations by assessing the 2,430 rupture scenarios for a single site and building model. The aggregated rate of exceedance amongst the rupture scenarios was the same as the annual rate of exceedance using the ground motions from the 2014 USGS National Seismic Hazard Maps (Peterson et al., 2014) for the same site, as expected.

## 4. BUILDING RISK VS REGIONAL RISK

Using the idealized building performance fragilities discussed above, we compare the building-level target performance objectives with the subsequent regional performance for the reoccupancy of the residential inventory using the simulated ground shaking data from all 2,430 rupture scenarios. We find that when buildings are designed to have a 10 % probability of exceeding 24-hour reoccupancy in 50 years, there is a 40 % chance that at least 5 % of the region will exceed a 24-hour reoccupancy time in a 50-year timeframe.

Indeed, even when we adjust the building-level fragility to reflect various performance objectives, the risk of exceeding the regional risk is typically much larger, as shown in Figure 5. Based on this assessment, the performance of individual buildings would need to have less than a 2 % probability of exceeding 24-hour reoccupancy in 50 years, to meet the 10 % in 50-year regional exceedance rate implied by the SPUR resilience plan. This trend indicates that building-level risk is not equal, nor similar to regional risk, given how geospatial variation of ground shaking affects a regionally dispersed collection of independent buildings for any given earthquake rupture scenario.

However, the specific relationship between building-level and regional risk is likely influenced by several key factors, including the community threshold, the shape of the fragility curve, the target recovery time, and the specific distribution of assets and size of the region. We explore some of these concepts in the next section.

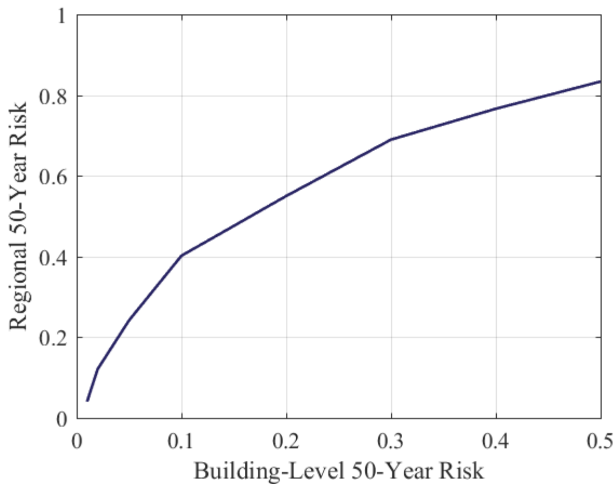


*Figure 5 – Probability of exceeding the community threshold for acceptable reoccupancy in 50-years (regional risk) for various building-level target performance objectives.*

## 5. SENSITIVITY ANALYSIS

In this section, we explore how various assessment assumptions influence the relationship between building- and regional-level risk. To start, we reassess the regional risk of the residential building stock by recalculating the idealized building-level fragility assuming lognormal dispersions ranging from 0.2 to 0.8, associated with the bounds of dispersion values estimated in preliminary assessment (Figure 2). We find that the assumed beta value has some influence on the overall relationship between building risk and regional risk, especially as building-level risk targets are relaxed (increase), as shown in Figure 6. As the uncertainty in building capacity reduces, the regional risk tends to become closer to building-level risk. In fact, if there was no uncertainty in building capacity, and all buildings experienced the exact same shaking intensity, there would be no difference between building risk and regional risk. As uncertainty in building recovery capacity is reduced, building-to-building recovery response effectively becomes more correlated throughout the region. Highly independent building response throughout the region leads to a high probability that some small number of buildings will be damaged and exceed the 5 % community threshold. On the other hand, correlated building response reduces these occurrences, depending on the specific community threshold. Even for a wide range of building-level dispersion (0.2 to 0.8), regional-risk still tends to be larger than building-level risk.

The choice of recovery time target directly impacts the lognormal dispersion of the idealized building performance fragility, thereby affecting regional risk in a similar fashion. In general, we observe that short recovery time targets will have smaller dispersions compared with long recovery time targets. Therefore, going from a recovery time target of reoccupancy within 24 hours, to a recovery time target of functional recovery within four months, will increase the building performance dispersion and widen the difference between building-level risk and regional risk, following the above trends in building fragility dispersion.

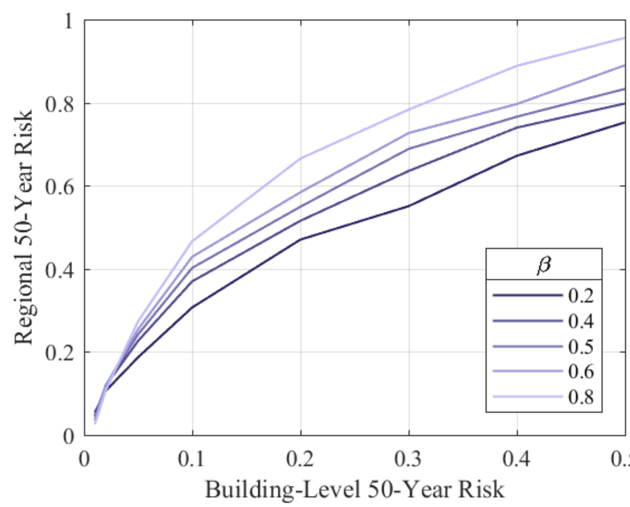


*Figure 6 - Impact of the lognormal dispersion of the building recovery fragility on regional risk.*

Another factor that plays a significant role in the relationship between building-level risk and regional risk is the community threshold. In the SPUR report, the choice of 5 % loss of residential inventory was selected based on the residential vacancy rates specific to City of San Francisco. However, other regions and building occupancies may have very different thresholds required to mitigate long term community recovery consequences. In Figure 7, we see that a more relaxed community threshold, such as those in the 20-50 % range, have a closer relationship between building risk and regional risk, in fact, even inverting the trend in some cases. Therefore, if we investigated a community threshold that required 50 % of office buildings to be functional within four months, as proposed by SPUR, the regional risk of exceeding that target may be much closer to the risk of exceeding a similar target on the building level.

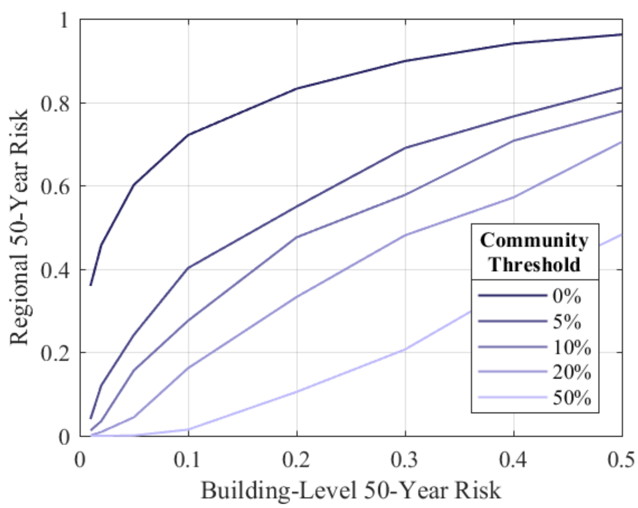


*Figure 7 - Impact of the community threshold on regional risk.*

## 6. CONCLUSIONS

To explore the relationship between building-level, recovery-based target performance objectives and regional recovery, we perform a probabilistic regional seismic loss analysis to quantify the regional risk of a collection of residential buildings in downtown San Francisco. This assessment facilitated a direct comparison between building-level risk-targets for recovery-based performance objectives and subsequent regional risk outcomes. We find that for previously proposed building-level risk targets of 10 % in 50 years, and community thresholds of no more than 5 % of the building stock exceeding acceptable recovery times, the regional risk of failure was significantly higher than the individual building risk of failure.

Indeed, this tended to be the case for most building-level target performance objectives (risk targets), community thresholds, and fragility curve idealizations. In fact, major variations in the assumed lognormal dispersion of the fragility curve had only moderate impact on regional performance, and only regional performance thresholds greater than 20 % tended to generate regional risks that were equivalent or smaller than individual building risk.

This study reflects a simple comparison between target building performance and regional performance using a relatively small set of residential buildings in a geographically localized area; outcomes from this study will likely differ for larger regions and differing seismic settings. In fact, extremely geographically dispersed assets would have very little regional risk as it would be unlikely for any one earthquake to impact a significant portion of the building stock. Additionally, actual community recovery will be affected by complex regional factors such as lifeline recovery and socio-economic recovery in the region; here, we only consider the impact of the distribution of buildings and ground shaking across the region. This study quantifies the regional performance given a target building-level performance objective, and therefore is not meant to be an assessment of an existing inventory of buildings.

This study shows that the community threshold for acceptable loss of building occupancy throughout the region plays an important role in the relationship between building risk and regional risk. Therefore, these types of factors may be informative in the selection of building-level performance targets for future building codes. While it is unclear exactly what the building-level recovery targets should be for future recovery standards, it is clear that the target performance defined for individual buildings may not directly imply an equivalent level of regional performance.

## 7. ACKNOWLEDGEMENTS

We would like to specifically acknowledge Dr. Anne Hulsey for graciously sharing her building inventory data, which was instrumental in conducting this study.

Certain commercial software may have been used in the preparation of information contributing to this paper. Identification in this paper is not intended to imply recommendation or endorsement by NIST, nor is it intended to imply that such software is necessarily the best available for the purpose.

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