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2.4 SEISMIC DESIGN OF BUILDINGS FOR FUNCTIONAL RECOVERY

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RESILIENCE PATHWAYS

CO-CREATING NEW KNOWLEDGE FOR UNDERSTANDING RISK AND RESILIENCE IN BC

This article is part of the Resilience Pathways Report. The report has the following objectives: a) to share knowledge about existing practices and recent advances in understanding and managing disaster and climate risk in BC, including some information on relevant federal programs, and b) to provide insights on gaps and recommendations that will help build pathways to resilience in BC.

This article belongs to *Chapter 2 Climate and Disaster Risk Management: Practice*. To read all articles in the report, see DRRPathways.ca.

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2.4 SEISMIC DESIGN OF BUILDINGS FOR FUNCTIONAL RECOVERY

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POST-EARTHQUAKE RECOVERY OF BUILDINGS

OVERVIEW

Prompt post-earthquake recovery of buildings is an integral component of a community's seismic resilience. As defined by EERI, "functional recovery is a post-earthquake state in which capacity is sufficiently maintained or restored to support pre-earthquake functionality."[1] Functional recovery of buildings enables people to return to their homes and facilitates access to other essential functions such as schools, healthcare, and commerce.[2,3] Nevertheless, past earthquakes have highlighted that building performance is generally inadequate to ensure the seismic resilience of communities. After the Kobe earthquake in 1995, roughly 15,000 households (19% of those impacted) relied on temporary housing three years after the earthquake.[4] After the Northridge earthquake in 1994, 33% of the damaged multi-family housing units, approximately 890 buildings, took more than two years to complete repairs.[5,6] One year after the L'Aquila earthquake in 2009, only 4% of 427 buildings surveyed had completed repairs, 29% had ongoing repairs, and the remaining 67% had not yet started repairs (Figure 1).[7]

While modern seismic design codes intend to ensure life-safety in extreme earthquakes, in recent years, planners and policy makers have directed a concentrated research effort to achieve better-than-code seismic performance. Functional recovery—the performance state of a building wherein it maintains or regains the ability to perform its basic intended use—is gaining significant importance.[8] In the US, the National Institute of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA) are developing performance objectives in terms of post-earthquake recovery times.[9,10] FEMA P-2082 has also recommended making functional recovery the primary basis for seismic design by assigning target recovery times (ranging from hours to months) to every new building, depending on the building's risk category.[11] Similarly, SPUR (San Francisco Planning and Urban Research) has identified target post-earthquake recovery times for a resilient San Francisco.[12] Despite these efforts, the efficacy of these resilience-based performance objectives is dependent on the availability of tools to assess the post-earthquake recovery time of buildings.

To expedite post-earthquake recovery, design targets in building codes should extend beyond the life-safety performance objective in extreme earthquake events to include resilience-based performance measures. These design targets and related performance measures should describe: 1) the ability to withstand earthquake loads without degradation or loss of function (i.e., robustness); and 2) the ability to regain functionality within a specified timeframe (i.e., rapidity).[13]

This article provides an overview of existing tools to estimate the post-earthquake recovery time of buildings. While the use of these tools presents a great opportunity, the importance of understanding the modelling assumptions and limitations cannot be overstated. These tools primarily serve to assess different structural and non-structural design options to enable the seismic design of buildings for enhanced performance, and to inform building owners of the expected earthquake performance as related to functional recovery. However, the results should not be regarded as hard truths, but rather as data to support effective decision making.

Figure 1 : In 2019 in L'Aquila, Italy, buildings in the historic centre were still undergoing restoration after the 2009 earthquake (Photo: Daniele Gussago/Shutterstock).

While modern seismic design codes intend to ensure life-safety in extreme earthquakes, in recent years, planners and policy makers have directed a concentrated research effort to achieve better-than-code seismic performance. Functional recovery—the performance state of a building wherein it maintains or regains the ability to perform its basic intended use—is gaining significant importance.

Pathways to the adoption of seismic design guidelines for the functional recovery performance of buildings in British Columbia are also discussed. This includes some commentary on new provisions in the 2020 edition of the National Building Code of Canada[14] related to an enhanced performance objective of "no structural damage" for a subset of all new buildings, for lower-level earthquakes, which is a positive move towards addressing the functional recovery objectives discussed herein.[i]

ALIGNMENT WITH THE SENDAI FRAMEWORK

The Sendai Framework for Disaster Risk Reduction 2015–2030 outlines four priorities for action to prevent new and reduce existing disaster risks: 1) Understanding disaster risk; 2) Strengthening disaster risk governance to manage disaster risk; 3) Investing in disaster reduction for resilience; 4) Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction. As previously defined, "functional recovery is a post-earthquake state in which capacity is sufficiently maintained or restored to support pre-earthquake functionality." As such, enabling the seismic design of buildings to achieve functional recovery enables people to return to their homes and facilitates access to other essential functions such as schools, healthcare, and commerce in the aftermath of a damaging earthquake. Designing buildings to achieve functional recovery performance enables disaster risk reduction by minimizing losses in lives, livelihoods, and in the economic, physical, social, cultural, and environmental assets of persons, businesses, and communities, resulting in direct alignment with the Sendai Framework for Disaster Risk Reduction.

[i] For brevity, this article focuses primarily on new building design, as enhancing the seismic performance of existing buildings to achieve functional recovery objectives presents further challenges.

EXISTING TOOLS TO ASSESS FUNTIONAL RECOVERY

Until recently, no tools were readily available to estimate the time required for a building that experienced damage in an earthquake to achieve a desired recovery state (e.g., functional recovery). Over the past decade, a growing number of frameworks have been developed to assess the anticipated seismic performance of buildings:

- The FEMA P-58 methodology,[15] a seismic performance assessment tool for individual buildings, translated engineering demand parameters (e.g., storey drifts and floor accelerations) obtained from structural analyses into performance metrics such as casualties, economic loss (repair costs), and repair time.

- The Resilience-based Earthquake Design initiative (REDi)[16] advanced the FEMA P-58 methodology by developing a framework to estimate the downtime of individual buildings to a defined recovery state by aggregating the repair time of damaged components, the delay time to start repairs, the effect of utility disruption, and other "impeding" factors.

- Developed more recently, TREADS[17] is a framework to probabilistically model the post-earthquake recovery of buildings and provide quantitative seismic performance measures, expressed in terms of downtime.

- Similarly, the ATC-138-3 project published a preliminary methodology to assess seismic performance in terms of the probable functional recovery time of individual buildings subjected to a damaging earthquake. The ATC methodology maps component-based damage to system-level operations, and system-level performance to tenant and building level re-occupancy and function.

- Both TREADS and ATC-138-3[18] are extensions to the FEMA P-58 methodology that conceptually implement impeding factor delay estimates as defined in REDi.

FEMA P-58

FEMA P-58 proposed a seismic performance assessment methodology for individual buildings based on the performance-based earthquake engineering framework.[19,20] The methodology employs predefined fragility functions to predict damage states in building components from structural response parameters, such as storey drift and floor acceleration. Consequence functions translate these damage states into various performance metrics, such as casualties, repair costs, and repair times. Monte Carlo simulations are used to account for the high degree of uncertainty in the structural response parameters, damage state predictions, and consequence estimates.

While the repair cost estimation procedure employed in the FEMA P-58 methodology is well established, the repair time calculation only estimates the time required to achieve full recovery and does not consider any intermediate recovery states, such as re-occupancy or functional recovery. Two estimates of building repair time are provided: repair time in series (considering repairs in each floor in a building take place sequentially) and repair time in parallel (considering repair in all floors in a building occur simultaneously). The assumed workforce depends only on the building floor area and not on the extent of damage to the building, and the repair sequencing is simplified to consider repairs of only one trade at a time on a floor. While these assumptions do not provide a realistic representation of the building's repair sequencing, the series and parallel repair estimates may serve as lower or upper bounds for the expected repair time to achieve full recovery. More importantly, FEMA P-58 does not account for any possible delays prior to the initiation of repairs, such as contractor mobilization, financing, permitting, or repair design, which can be significant contributors to a building's downtime.[21]

REDi

The REDi guidelines extended the FEMA P-58 methodology and proposed a framework to estimate downtime in individual buildings to a defined recovery state. The developments include an estimate of the impeding factor delays between the occurrence of an earthquake and the start of repairs (e.g., inspection, financing, contractor mobilization, etc.), as well as estimates of utility disruption (e.g., electrical systems, water systems, etc.). The guidelines identify three post-earthquake recovery states: re-occupancy (building is safe enough to occupy), functional recovery (basic building functionality is restored), and full recovery (building is restored to its pre-earthquake condition). To identify the required repairs to achieve the desired recovery state, a repair class is assigned to each component in the building based on its extent of damage.

While the guidelines represent a significant contribution to downtime quantification, there are several limitations, such as conservative re-occupancy criteria, worker allocation, and repair sequencing. The REDi guidelines use the re-occupancy recovery state to determine if a building is safe enough to occupy—if it can be used for shelter. However, the structural and non-structural component recovery criteria suggested to achieve this recovery state seem overly conservative. According to the guidelines, repairs of almost all structural, plumbing, and HVAC components must be completed before a building can be occupied. By contrast, several researchers recommend that sheltering criteria for buildings in a post-disaster setting should consider relaxed habitability standards that allow people to stay in their own homes—even if damaged—after an earthquake, as long as the building does not pose a life-safety risk.[22,23]

To help define the order of repairs to be conducted, the REDi guidelines segregate all non-structural repair activities into groups of repair sequences. The guidelines consider that repair activities begin with the building's structural components and repair progresses only one floor at a time. The non-structural repair commences only after the entire building's structural repairs are complete. In contrast with this assumed approach, after the 1994 Northridge earthquake, contractors often repaired several floors simultaneously and performed elevator and staircase repairs in parallel with structural repairs.[24]

TREADS

TREADS (Tool for Recovery Estimation And Downtime Simulation) is a framework to probabilistically model the post-earthquake recovery of buildings and provide quantitative seismic performance measures, expressed in terms of downtime, that are useful for decision making.

Downtime estimates include the time for mobilizing resources after an earthquake and for conducting necessary repairs. The TREADS framework advances the well-established FEMA P-58 and REDi methodologies by modelling temporal building recovery trajectories to different recovery states. Analogous to safety-based US codes, which specify a threshold for the probability of collapse under a given ground motion shaking intensity (e.g., 10% or less probability of collapse under the risk-targeted maximum considered earthquake), this framework permits evaluating the probability of a building not achieving a target recovery state (e.g., shelter-in-place immediately after the earthquake), or, alternatively, the probability of not achieving a target recovery state (e.g., functional recovery), within a specified time frame.

The framework leverages the damage state predictions and component repair times obtained from the FEMA P-58 analysis to estimate building performance in terms of downtime. This process consists of five sequential steps:

1. Evaluate the extent of damage and identify the post-earthquake usability of the building, considering five distinct recovery states immediately after the earthquake: stability, shelter-in-place, re-occupancy, functional recovery, and full recovery. The shelter-in-place recovery state accounts for relaxed post-earthquake habitability standards, in contrast with the re-occupancy recovery state, which relates to pre-event habitability criteria.
2. Evaluate impeding factor delays—the various factors that may delay or impede the initiation of repair activities. These activities include the time required for building inspection, securing financing, arranging engineering services and designs, obtaining permits, mobilizing a contractor, and performing repairs to stabilize the structure or the building envelope (i.e., mitigation work to minimize aftershock collapse risk and falling debris hazard).
3. Assess the building's repair time to achieve the desired recovery state.
4. Model the building's time to recovery by using the delay time and repair time estimates, providing downtime estimates for each storey in the building. (To account for the various uncertainties within the downtime estimation procedure, the first four steps are performed for thousands of Monte Carlo simulations, resulting in thousands of downtime realizations (plausible outcomes) and recovery trajectories, each having an equal likelihood of occurrence, as illustrated in Figure 2.)
5. Link the downtime estimates to probabilistic performance measures (robustness and rapidity) that support decision making by building owners, engineers, and policy makers.

Each of the recovery states considered by TREADS represents a milestone in a building's overall recovery trajectory. To estimate downtime to achieve each of these recovery states, the framework uses the repair class concept introduced by the REDi guidelines. The damage state of each building component in each realization is tagged with a repair class, which serves to identify the recovery state hindered by the damage extent to

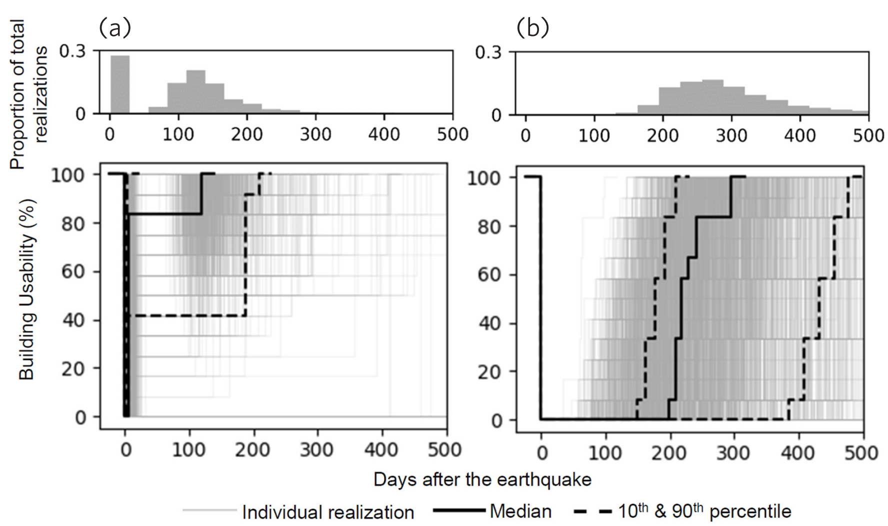

Figure 2: Recovery trajectories to (a) shelter-in-place and (b) functional recovery for 1000 realizations of building performance under ground motion shaking with a return period of 975 years (adapted from Molina Hutt et al, 2022).

the component. The post-earthquake usability is determined by identifying the recovery state achieved by the building immediately after the earthquake, before any recovery activities begin. The building condition when each of the recovery states is achieved and the associated repair class is shown in Table 1. Components that are damaged to a level that hinders achieving the building condition outlined in the table will need to be repaired before the recovery state can be achieved.

To illustrate this concept, consider a reinforced concrete shear wall building. The structure's slender shear walls are characterized by a fragility function with three distinct damage states. Damage state DS1 represents spalling of the cover with vertical cracks greater than 1/16 of an inch, which is tagged with a repair class RC3 and hinders achieving the re-occupancy recovery state. Damage state DS2 represents exposed longitudinal reinforcing and triggers an unsafe placard per the FEMA P-58 methodology, hence is tagged with a repair class RC4 and hinders achieving the shelter-in-place recovery state. Damage state DS3 represents concrete core damage or buckled/ fractured reinforcing. Because this is believed to compromise the load carrying capacity of the member, it is linked to a repair class RC5 and hinders achieving the stability recovery state.

Within the proposed assessment framework, all component damage linked to a repair class equal to or

Table 1: *Recovery state, building condition, and repair class, in descending order of criticality (adapted from Molina Hutt et al, 2022)*

Recovery State	Building Condition[ii]	Repair Class[iii]
Stability	Significant structural and non-structural damage that does not compromise the building stability	5
Shelter-in-place	Moderate structural and non-structural damage that does not threaten the safety of residents	4
Reoccupancy	Cosmetic structural and moderate non-structural damage	3
Functional recovery	Cosmetic structural and minor non-structural damage	2
Full recovery	No damage, pre-earthquake functionality maintained or restored	1

greater than that associated with the desired recovery state, as indicated in Table 1, must be repaired before the recovery state in question can be achieved. To achieve functional recovery, for example, all components with repair classes RC2, RC3, RC4, and RC5 need to be repaired. If no[ii,iii] component damage hinders achieving the desired recovery state, the repair time to the recovery state in question is zero (e.g., if the maximum repair class across all structural and non-structural components is RC3, the repair time to shelter-in-place is zero).

TREADS[iv] permits calculating the following outputs and resilience-based metrics: 1) the recovery trajectory of the building showing the progress of building restoration, or reconstruction, over time; 2) the robustness, or "the ability [of the building] to withstand a given level of stress or demand without suffering degradation or loss of function;"[25] 3) the rapidity, or "the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption;"[26] and 4) the downtime disaggregation to help prioritize design or retrofit interventions to minimize downtime.

In addition to the recovery trajectories, previously illustrated in Figure 2, sample robustness and rapidity outputs are illustrated in Figure 3. While the terms "robustness" and "rapidity" are frequently used to measure the seismic resilience of communities, within the TREADS framework, the terms measure seismic performance of individual buildings. Figure 3a illustrates the probability of not achieving the shelter-in-place

[ii] *Describes the state of the building when the recovery state is achieved.*

[iii] *Indicates the minimum repair class that hinders achieving the corresponding recovery state.*

[iv] *TREADS is fully compatible with the SimCenter's (the computational modelling and simulation center of the Natural Hazards Engineering Research Infrastructure program) tool for loss assessment, PELICUN, an open-source application that implements the FEMA P-58 methodology. Thanks to this compatibility, a user can perform a complete damage, loss, and downtime assessment within a unified workflow. The TREADS framework coded in Python is available as an open-source application at the following Github repository: https://github.com/carlosmolinahutt/treads. TREADS is also available at the Python Package Index (PyPI) and can be easily installed using pip. See A. Zsarnoczay and P. Kourehpaz P, NHERI-SimCenter/pelicun: pelicun v2.5 (Version v2.5), 2021.*

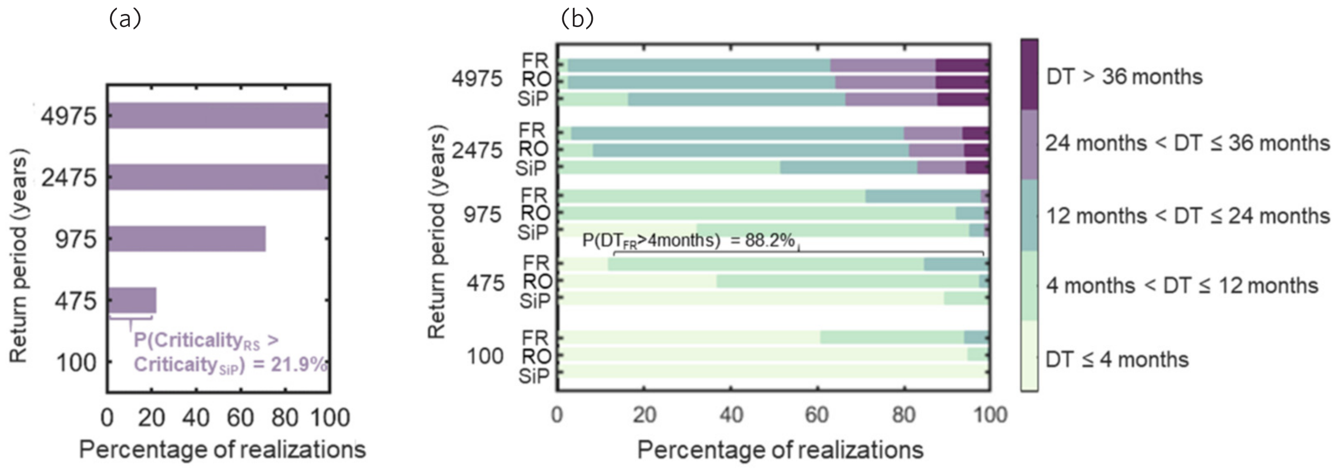

Figure 3: Sample assessment outputs under a range of hazard levels with low to high probabilities of exceedance (high to low return periods) including: (a) Robustness or the probability of not achieving the shelter-in-place recovery state immediately after the earthquake, and (b) Rapidity or the downtime to achieve functional recovery (FR), re-occupancy (RO), and shelter-in-place (SiP) recovery states within specified time frames (adapted from Molina Hutt et al, 2022).

recovery state immediately after the earthquake (ground motions representative of a range of hazard levels with low to high probabilities of exceedance). Figure 3b summarizes the downtime to achieve functional recovery (FR), re-occupancy (RO), and shelter-in-place (SiP) recovery states (also across a range of ground motion shaking intensity levels). If the building design does not conform with the desired performance measures, the framework also provides a disaggregation of downtime that highlights the components that contribute to inadequate performance, thus enabling effective design interventions.

ATC-138-3

As described in the ATC-138-3 Preliminary Report,[27] this methodology[v] for assessing functional recovery time utilizes the architecture of FEMA P-58 to explicitly quantify the loss of building function and the time to restore it. The method defines a new re-occupancy and building function module to the FEMA P-58 process, which maps component-based damage to system-level operations, and system-level performance to tenant and building level re-occupancy and function.

This new logic is implemented as a series of fault trees. In defining recovery time, the framework conceptually adopts the REDi impeding factors and certain aspects of repair scheduling proposed in the REDi guidelines and by Terzic and Yoo in 2016.[28] The recovery states tracked in this methodology are re-occupancy, functional recovery, and full functionality. While the ATC-138-3 definition of functional recovery is consistent with that employed in the TREADS framework, the ATC-138-3 definition of re-occupancy is consistent with TREADS's shelter-in-place, and full functionality in ATC-138-3 corresponds to full recovery as defined in the TREADS framework.

The general approach and logic for assessing building function is illustrated in Figure 4. First, for a building to be functional, the building must be safe to enter and re-occupy. Then, each storey of the building must be accessible, and tenants must be safe from falling and other safety hazards. Finally, tenant units within the building must be able to provide their basic intended functions within the tenant space. As illustrated in Figure 4, in "Stage 1: Building Safety," the building is evaluated for occupant safety hazards that would cause the whole building to be shut down. This check identifies whether damage

[v] The source code associated with the ATC-138-3 methodology is freely available at https://github.com/dcook519/PBEE-Recovery. The computational algorithms have also been implemented by HB-Risk in their SP3 software modules, which are available at www.sp3risk.com.

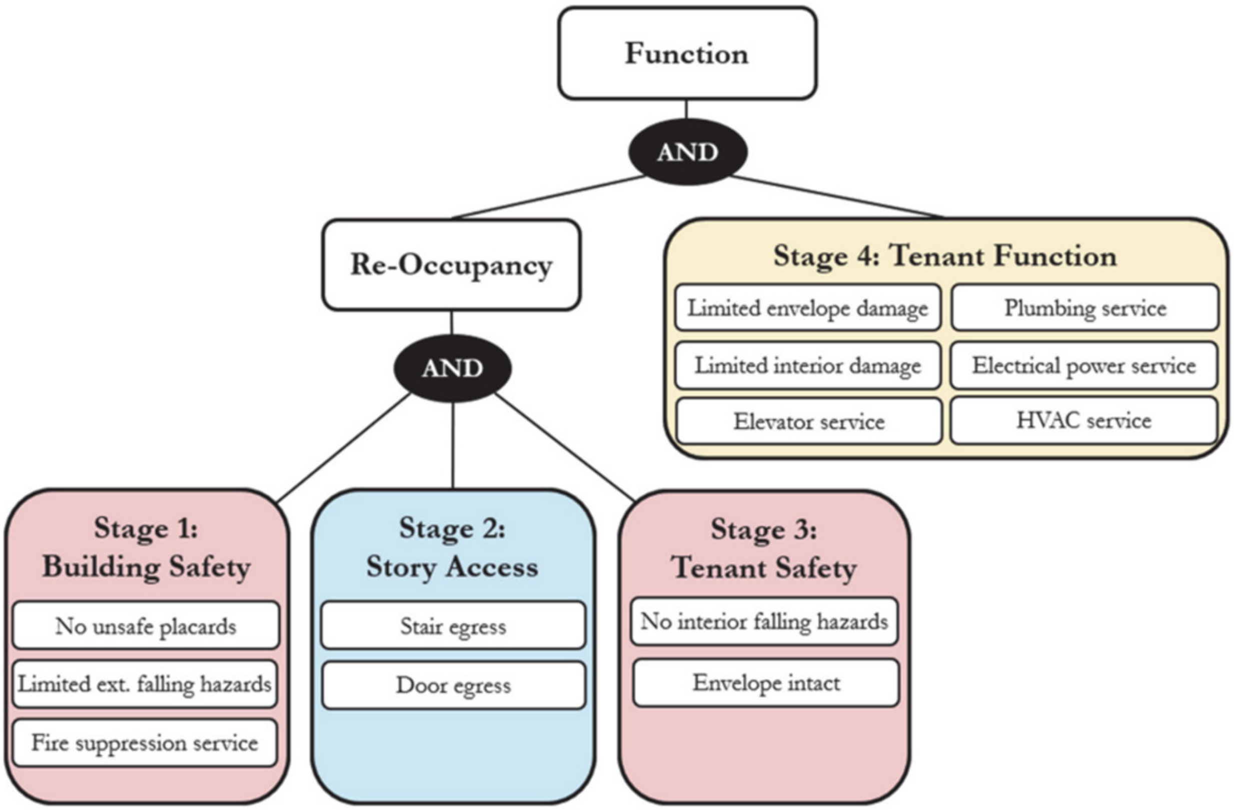

Figure 4: ATC-138-3 logic tree framework for assessing functionality (ATC-138-3, 2021).

exists that can lead the entire building to being classified as unsafe to occupy (e.g., structural safety concerns, external falling hazards). In "Stage 2: Storey Access," each storey is verified for egress and access routes, based on damage to stairways and doors. "Stage 3: Tenant Safety," identifies local safety issues, such as interior falling hazards, in tenant units within the building. Finally, "Stage 4, Tenant Function," checks whether building systems are in a condition such that the tenants can function in the space. Stages 1, 2 and 3 are required for re-occupancy of a particular space. In addition to these, Stage 4 is required for function to be restored.

As outlined in the ATC 183-3 preliminary report, the functional recovery methodology recognizes that building function may imply unique requirements for each tenant within the building, and, therefore, breaks down the building into tenant units and quantifies the functional performance of each tenant-unit individually. Building-level functional performance is quantified as the collection of the functional performance of all tenant units within the building. In each stage, component damage is related to system-level function based on a series of fault trees. These fault trees are used to define the effect that component damage has on the condition or operation of different building systems, based on assumptions as to how the condition or operation of each system affects the re-occupancy or functionality of each tenant unit. In the last stage, the function of each tenant unit is determined based on whether the performance of each system meets, or fails to meet, tenant-specific functional requirements. Figure 5 illustrates a sample fault tree employed to define the performance of the interior system in "Stage 4: Tenant Function." Similar fault trees are employed to assess other building systems, such as HVAC, electrical power, plumbing or elevators.

While the ATC-138-3 preliminary report was recently made publicly

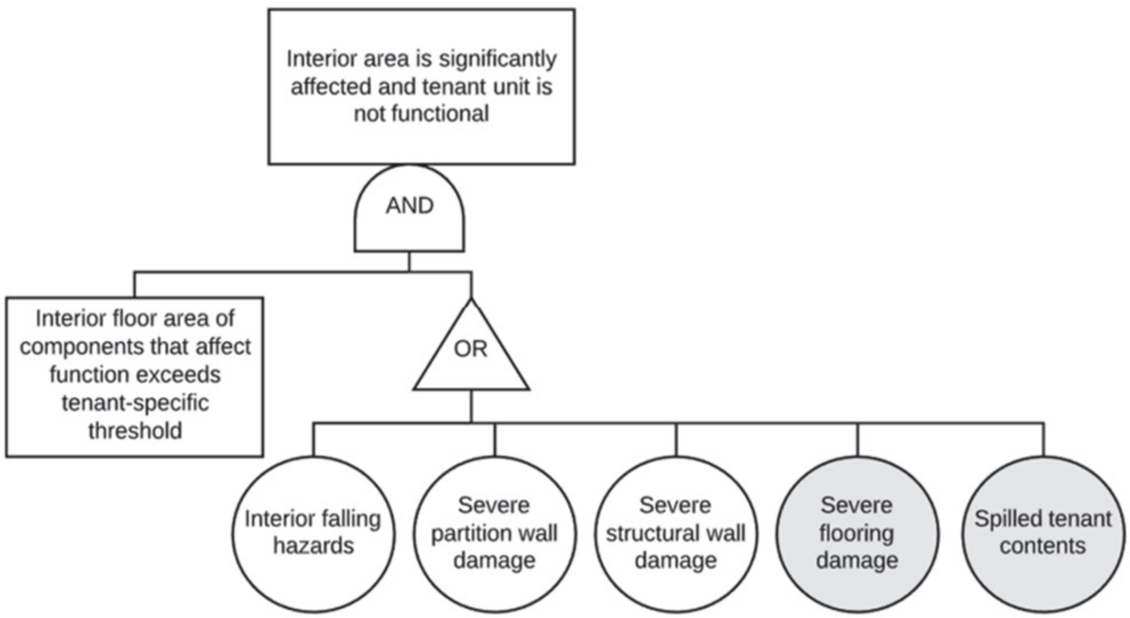

Figure 5: Fault tree defining the performance of the interior system for the Tenant Function stage (Stage 4). Gray events are not currently considered in the framework (ATC-138-3 2021).

available, to date no case studies have been published to demonstrate the implementation of the proposed framework. As new methodologies are developed, there is a clear need for comparative studies that evaluate the functional recovery performance (among other resilience-based metrics) of range of case study buildings leveraging different frameworks to enable moving towards a consensus-based approach.

OPPORTUNITY

PATHWAYS TO IMPLEMENTATION IN BC

The 2015 edition of the National Building Code of Canada,[29] adopted for the most part in the 2018 edition of the BC Building Code and the 2019 Vancouver Building By-law, is an objective-based code with varying earthquake performance objectives according to the importance category of buildings, which are set as a function of intended use and occupancy. For instance, buildings that are essential in the event of a disaster, such as hospitals, are termed "post-disaster buildings" and correspond to the highest importance category. As a result, the seismic design of these buildings includes an importance factor of 1.5. Buildings that are likely to be used as post-earthquake shelter, such as schools, have a high importance category and, in turn, an importance factor of 1.3. By contrast, buildings with a normal importance category have an importance factor of 1. The use of higher importance factors intends to achieve three things: 1) provide reduced damage to the structure; 2) provide reduced damage to elements, non-structural components and equipment (also known as operational and functional building components) and their connections; and 3) minimize residual structural drift by the requirement of reduced peak transient storey drift limits.

The design-level earthquake according to the National Building Code is equivalent to ground motion shaking with a 2% probability of exceedance in 50 years. Despite defining a single design earthquake level, the resulting performance of buildings designed according to this standard could vary widely.[vi]

[vi] This variation in performance is attributed to the large number of seismic force resisting systems available in the code with different Rd values (ductility-related force modification factors reflecting the capability of a structure to dissipate energy through reversed cyclic inelastic behavior

The implicit performance objectives of the National Building Code are to: 1) protect the life and safety of building occupants for the code-level earthquake; 2) limit building damage due to low-to-moderate levels of shaking; and 3) increase the chances of post-disaster buildings being functional and occupiable after strong ground shaking.[30] Referring back to the recovery states introduced in Table 1, and considering the range in anticipated seismic performance previously discussed, when subjected to ground motion shaking consistent with the design-level earthquake, buildings with a normal importance category are most likely to achieve stability, high importance category buildings might achieve shelter-in-place, and post-disaster buildings would likely achieve the top range of shelter-in-place nearing the re-occupancy recovery state.

The 2020 edition of the National Building Code[31] introduces additional requirements for post-disaster and high importance category buildings, as well as a subset of buildings with a normal importance category—those with heights above grade greater than 30 metres. These requirements are applicable to structures in areas of moderate to high seismicity, expressed in terms of seismic category in the new edition, and introduce additional design requirements at a lower hazard level (an earthquake more frequent than the design level, with ground motion shaking with a 5%–10% probability of exceedance in 50 years). The additional requirements include ensuring the structure and the connections of operational and functional components (OFCs) behave elastically (no structural damage and undamaged OFC connections), and also includes stricter drift limits that minimize seismic damage to non-structural components at these lower levels of ground shaking. Ultimately, these new requirements reduce the variation in anticipated seismic performance across seismic force resisting systems under the hazard levels considered (because the structure is undamaged) and would implicitly result in seismic performance consistent with the functional recovery state, previously defined in Table 1.

While these new design requirements can bring us closer to achieving desirable recovery states for selected levels of earthquakes, the evolution of codes to further address recovery states will be a slow process as new editions are updated only every five years. Therefore, code efforts should be complemented by the various frameworks presented herein. The availability of these frameworks to estimate downtime to functional recovery (or other recovery states) means that explicit consideration of these performance measures for use in building design is now a possibility. Training of all involved in the building industry on the use of these methodologies, as well as education of and outreach to the general public to enhance their understanding of earthquake risk and recovery-based objectives, is vital to improving how our buildings are designed and constructed.

The evolution of codes to further address recovery states will be a slow process as new editions are updated only every five years. Therefore, code efforts should be complemented by the various frameworks presented herein.

In BC, there may be unique pathways to the adoption of enhanced seismic design requirements to achieve functional recovery objectives. In contrast with other municipalities in BC, the City of Vancouver via the Vancouver Charter can set its own Building By-law independent from the BC Building Code, and the University of British Columbia has its own Building Regulations that do not need to comply with the BC Building Code. This independence provides an opportunity to raise the bar by enhancing earthquake design and performance requirements and serve as an example for the BC Building Code or the National Building Code of Canada, the latter of which serves as the model code for the provinces and territories. A shift from an

via expected localized damage). For example, a concrete ductile shear wall building with an Rd of 5 will have a different performance compared to a steel concentrically braced frame with an Rd of 2. While all of these systems meet the minimum requirements of the code, they perform in very different ways in terms of their anticipated ductility and damage level.

implicit to a more explicit verification of a building's seismic performance would also align with other current efforts considering a transition from objective-based to performance-based building codes.

While such shifts in our design philosophy may be foreign to some, there already are examples of projects in BC that utilized the tools presented here. For instance, the FEMA P-58 methodology is currently being used in the high-profile St. Paul's Hospital project in Vancouver, where design requirements include specific FEMA P-58 metrics (repair costs, repair times, etc.) for different levels of shaking, introduced as part of a rezoning condition.[32] The outputs of the FEMA P-58 assessment are provided to help the owner understand the expected damage state of building components on a floor-by-floor basis and the potential impacts on building occupancy and functionality. Similarly, the University of British Columbia is utilizing the REDi rating system to provide guidance to project teams in achieving resilience, and UBC has ongoing retrofit projects that aim to achieve a high resilience level of "immediate occupancy" following a major earthquake.[33]

FEMA P-58 AND REZONING ST. PAUL'S HOSPITAL

As part of the City of Vancouver's rezoning process for the new St. Paul's Hospital (Figure 6), a "Resilience Rezoning Condition" was created. This condition required the proponent to perform a climate risk assessment and a seismic assessment to inform facility design and operations with the goal of advancing likely post-disaster building functionality (and patient safety) in response to the impacts of both climate change and seismic events.

Figure 6: Concept of the new St. Paul's Hospital in Vancouver (Illustration: flickr/Province of BC).

The climate assessment followed a hybrid methodology of the PIEVC protocol, Climate Lens, ISO 31000 Risk Management, and the ICLEI BARC tool. FEMA's P-58 standard was used for the seismic assessment—a first for a hospital in Canada.

Outputs of this seismic assessment exceeded the resolution of the BC Building Code by providing proxies for the building's likely functionality (e.g., seismic damage, repair costs and repair times) following a major earthquake. This form of seismic assessment, performed during the design process of new buildings, is a potential strategy to advance high-performance buildings more broadly. The process of assessment provides design teams and developers invaluable information so that they may make performance-based design decisions to meet functionality expectations within, but also possibly above and beyond, the life-safety protection minimum requirement currently in the code.

RECOMMENDATIONS

Table 1: Recommendations

Recommendation	Description of Impact	Priority Level	Capabilities Needed
1. Train all involved in the building industry on the use of these methodologies; educate and engage with the public to enhance their understanding of earthquake risk and recovery-based objectives.	Training enables the delivery of building projects in which the expected seismic performance of buildings expressed in terms of their functional recovery is explicitly verified. Outreach results in direct demand from end-users (building owners and occupants) for buildings with enhanced seismic performance.	Critical	Technical and financial
2. Raise the bar by enhancing earthquake design and performance requirements.	The ability of the City of Vancouver and UBC to set their own bylaws independent of the BC Building Code or the National Building Code of Canada, which serves as the model code for the provinces and territories, provides a unique opportunity to raise the bar by enhancing seismic design and performance requirements.	Critical	Leadership
3. Shift from objective-based to performance-based design.	Shifting from the current implicit verification of a building's seismic performance (i.e., building meets code) to an explicit verification of performance (e.g., the building will take five days to achieve functional recovery after a major earthquake) will enhance our understanding of earthquake risk and will engage end-users (building owners and occupants) in defining the desired seismic performance of buildings.	Recommended	Technical and legislative (reflect in code)

CHALLENGES

Addressing the following three challenges will be necessary to advance the functional recovery of buildings.

1. **Cost:** The cost associated with the design of buildings to achieve enhanced seismic design requirements is a known challenge. But case studies[34] and research[35] suggest that the cost premium is small and there is a benefit to raising the bar if one were to consider costs from a lifecycle perspective as opposed to simply upfront or initial design and construction costs.

2. **Reaching a consensus-based approach:** New frameworks to evaluate downtime and functional recovery performance of buildings are just that—very new; they require a large number of assumptions and are yet to be tested or assessed against empirical data collected after major earthquakes, which allows us to check how our analysis results compare to reality. As a result, it will take time for the engineering community to embrace these new concepts and, more importantly, to reach consensus on how to conduct these assessments to ensure

consistency in our approach. The slow evolution of codes referenced in the article is in part related to this notion of the difficulty in reaching consensus.

3. **Existing buildings:** While adopting these design requirements and procedures for new building design might be challenging, applying these to existing buildings raises an even greater challenge. Existing buildings need only comply with the requirements of the code at the time they were designed and constructed. Updated editions of the building code are not applied retroactively to existing buildings. Therefore, the seismic upgrade of existing buildings could be costly and difficult to implement other than on a voluntary basis.

Training of all involved in the building industry on the use of these methodologies, as well as education of and outreach to the general public to enhance their understanding of earthquake risk and recovery-based objectives, is vital to improving how our buildings are designed and constructed.

RESOURCES

INTERNATIONAL

1. More information on the key frameworks discussed:

FEMA P-58

FEMA. *Seismic performance assessment of buildings FEMA P-58.* Washington, DC: Federal Emergency Management Agency, 2012. https://femap58.atcouncil.org/documents/fema-p-58/24-fema-p-58-volume-1-methodology-second-edition/file.

REDi

Almufti, I. and M. Willford. "REDi™ Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings." San Francisco: Arup, 2013. https://www.redi.arup.com/.

TREADS

Molina Hutt, C., T. Vahanvaty, and P. Kourehpaz. "An analytical framework to assess earthquake induced downtime and model recovery of buildings." *Earthquake Spectra* (2022, in press). https://journals.sagepub.com/doi/full/10.1177/87552930211060856.

ATC-138

Applied Technology Council (ATC). "Methodology for Assessment of Functional Recovery Time, A Preliminary Report." *Seismic Performance Assessment of Buildings*, Volume 8. FEMA, 2021. https://femap58.atcouncil.org/documents/fema-p-58/34-atc-138-3-volume-8-methodology-for-assessment-of-functional-recovery-time/file.

2. White paper on functional recovery:

Earthquake Engineering Research Institute (EERI). "Functional Recovery: A Conceptual Framework with Policy Options." Oakland: EERI, 2019. https://www.eeri.org/images/archived/wp-content/uploads/EERI-Functional-Recovery-Conceptual-Framework-White-Paper-201912.pdf

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