A Framework for Operationalizing the Assessment of Post-Earthquake Functional Recovery of Buildings

Dustin T. Cook M.EERI[1], Abbie B. Liel M.EERI[2], Curt B. Haselton M.EERI[3], Maria Koliou M.EERI[4]

Building damage after an earthquake, or other hazard event, can interrupt businesses, displace households, and significantly disrupt a community for years. As a result, policymakers and engineers are working towards new design guidelines and policies that reduce the vulnerability of the built environment through improved building functional recovery performance. This study proposes a method for assessing the post-earthquake building performance states of function and reoccupancy within the architecture of performance-based earthquake engineering, targeted at U.S. construction, and making use of FEMA P-58 fragility and consequence models. This is accomplished by mapping component damage states to systems-level operational performance, and then to building-level performance states, through a series of fault trees. The study also proposes a repair scheduling algorithm to estimate the time taken to restore a building reoccupancy or function, considering impeding factors that delay the start of repairs. The result is a probabilistic approach that extends the performance-based engineering framework to explicitly quantify post-earthquake building function performance states, thus facilitating design and mitigation decisions for recovery-based performance objectives.

INTRODUCTION

Earthquakes, such as those in Loma Prieta (CA, 1989), Northridge (CA, 1994), and Christchurch (New Zealand, 2010/2011), have shown that modern seismic design codes for buildings generally meet life-safety goals. However, these same events have also demonstrated that modern standards may provide little protection against extensive damage that can lead to loss of use (Porter, 2016a). Indeed, damage to buildings and infrastructure in these same earthquakes significantly interrupted businesses, displaced families, and disrupted community economies and life for years after the earthquakes (Comerio, 2000; Mieler & Mitrani-Reiser, 2017). Experiences from other types of hazards, including hurricanes and wildfires, have

[1] PhD, PE, University of Colorado Boulder, and now at the National Institute of Standards and Technology
[2] Professor, Dept. of Civil, Environmental and Architectural Eng., University of Colorado Boulder
[3] Professor, Dept. of Civil Engineering, California State University, Chico
[4] Assistant Professor, Zachry Dept. of Civil and Environmental Eng., Texas A&M University

similarly demonstrated the long-term community impacts of extensive building damage (Miles & Chang, 2011), which disproportionately affect small businesses, and lower-income and minority residents (Kroll et al., 1991; Blaikie et al., 1994; Tierney and Dahlhamer, 1998; Alesch and Holly, 1998; Chang and Falit-Baiamonte, 2003; Van de Lindt et al., 2020).

Growing awareness of earthquakes' long-term implications for community resilience has motivated a paradigm shift in building design that involves moving beyond minimum requirements for life-safety to consider damage control and recovery of building function. For a building, functional recovery "means it is ready to support most of its pre-earthquake uses in addition to reoccupancy" (NIST & FEMA 2021; Sattar et al. 2020). To date, much of the work on functional recovery has focused on defining the concept of functional recovery and identifying factors that influence post-earthquake building function and recovery (e.g., NIST, 2018; EERI, 2019; Sattar et al., 2020; California Legislature, 2021; NIST & FEMA, 2021).

This paper proposes a method for operationalizing and quantifying building functional recovery for individual buildings, as a function of shaking intensity, building response, component damage, and building occupancy. The proposed method fits within the architecture of performance-based earthquake engineering (e.g., Porter, 2003; Deierlein & Moehle, 2004), adopting fragility and consequence models from FEMA P-58 (2012; 2018) to quantify damage to structural and nonstructural components within the building. The proposed method groups component damage into building systems (e.g., cladding, plumbing, electrical, etc.) and uses fault trees (e.g., Fussell et al., 1974) to define explicit relationships between component damage, system operation, and building function at the tenant-unit level, based on the physical characteristics of each system and component. The paper also develops a new set of impeding factors and repair scheduling algorithm to quantify the recovery of function over time.

DEFINITION OF FUNCTIONAL RECOVERY TERMS

Three building performance states are tracked in the proposed method: reoccupancy, function, and full repair (Bonowitz, 2011).

- *Building reoccupancy* is a building performance state that indicates the building is safe enough to be used for shelter (e.g., SPUR, 2012; Almufti and Willford, 2013; FEMA, 2019), meaning that, although it may lack critical systems that hinder function, it is habitable and safe.
- *Building function* is a building performance state that indicates that a building can be used for its "basic intended functions". According to the report submitted to Congress

by the National Institutes of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA), "Basic intended functions are less than full pre-earthquake functionality, but more than what would be considered the minimum sufficient for reoccupancy of buildings, or for temporary provision of lifeline services." For example, a "factory is ready to get back to business but might have reduced production capacity" (NIST & FEMA, 2021); this capacity can vary depending on a building's occupancy or use case, *e.g.,* patient waiting times in hospitals (Cimellaro & Piqué, 2016), or the floor area of usable space in an office building (Mitrani-Reiser et al., 2012).

- *Building full repair* is a building performance state that indicates all repairs are complete, including the repair of items not required for reoccupancy or function.

Recovery time refers to the time it takes to achieve a desired performance state after the disaster occurs (e.g., Almufti and Willford, 2013; EERI, 2019; FEMA, 2019; NIST & FEMA, 2021). The recovery time includes the time taken to make repairs, including any factors that delays the start of those repairs; the latter are referred to as *impeding factors* (Almufti, 2013). Accordingly, the *recovery trajectory* quantifies the level of building performance throughout the recovery time (e.g., Bruneau et al., 2003; Jacques et al., 2014; Burton et al., 2015; Mieler et al., 2016; Lin & Wang, 2017a), as illustrated in Figure 1. Thus, *functional recovery* is the combination of both the building's level of function—based on damage—and the building's recovery, and defines the time needed to achieve the building function performance state.

FUNCTIONAL RECOVERY: STATE OF ART AND PRACTICE

THE NEED TO DESIGN BEYOND LIFE SAFETY

Since the adoption of the first seismic design codes in the early 20th century, engineers have focused on improving the performance of buildings to withstand collapse and protect life-safety; consequently, casualty risk has generally reduced with the evolution of seismic building codes (Spence et al., 2011). However, it is also evident that designing buildings to protect life safety does not necessarily ensure adequate post-earthquake functional recovery. After the 1989 Loma Prieta (CA) Earthquake, for example, it took up to 10 years to repair damaged schools, housing, and highways, resulting in the permanent closure of many buildings (Comerio, 2006; 2014); on the Stanford University campus alone, 25 buildings were closed for up to three years, and two percent of campus space was permanently closed (Comerio, 2006). Due to damage from the 1995 Kobe (Japan) Earthquake, the region's population dropped by

2.5%, and the city lost 10% of its businesses, with an especially large impact on smaller businesses. It took over 10 years for the region to return to its pre-earthquake population (Chang 1996; 2010). After the 2011 Canterbury (New Zealand) Earthquake sequence, Christchurch's central business district remained closed for over two years, and 11% of the city's businesses permanently closed (Mieler et al., 2016). Analytical studies have also reached similar conclusions. Among others, Molina Hutt et al. (2019) and Liel and Deierlein (2013) showed that modern seismic design of steel and reinforced concrete moment frames has significantly reduced collapse risk relative to older designs, but only modestly reduced damage and economic losses. As a consequence, based on California data, Porter (2016b) estimated that, in an earthquake, for every collapsed building, there are about 63 buildings with impeded occupancy (indicated by a red or yellow tag). Given this ratio, Porter (2016b) projected that - without changes for functional recovery - 24% of households in San Francisco would be displaced by a hypothetical future magnitude 7.0 earthquake on the Hayward fault.

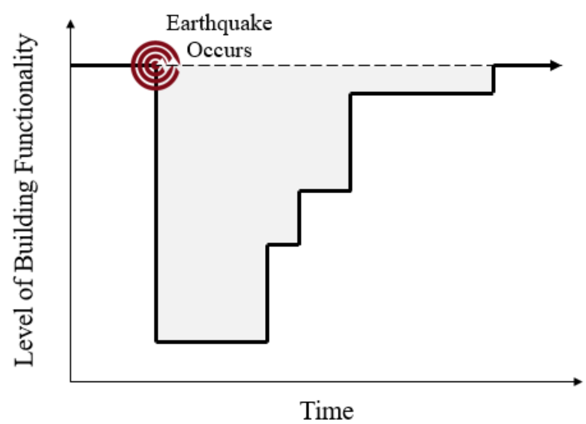

Figure 1. Illustration of a building's recovery trajectories for the building function performance state. Steps in the recovery trajectory coincide with repairs to various building systems that lead to recovery of function in one or more tenant units within the building.

Yet, the idea that buildings codes do not define requirements to limit damage and ensure recovery runs counter to public expectations. Davis & Porter (2016) surveyed around 500 adults in high seismic areas of the U.S, showing a significant fraction of those surveyed already believe that new buildings are designed to be occupiable and functional after earthquakes. A majority also indicated they would prefer occupiable and functional building performance targets, compared to the status quo, even if it resulted in increased construction and rental costs.

RECENT POLICY SHIFT TOWARDS FUNCTIONAL RECOVERY

Goals of enhancing community resilience through improved post-earthquake building functional recovery have motivated recent state and federal policy. As part of Congress' 2018

National Earthquake Hazards Reduction Program reauthorization, NIST was tasked to identify research needs and implementation activities that would improve building functional recovery (NIST, 2018). NIST identified four primary topics, encompassing building design, community considerations, economic and social considerations, and adoption considerations, and outlined potential frameworks for integrating functional recovery objectives into building codes. Around this time, the Earthquake Engineering Research Institute (EERI) also developed a framework that conceptually outlines implementation strategies to promote building designs with better functional recovery performance (EERI, 2019).

More recently, NIST and FEMA produced a report to Congress which outlines the need for functional recovery design and provides recommendations on how state and local agencies might implement such requirements to improve community resilience (NIST & FEMA, 2021). The report proposed a framework to extend building codes to assign target functional recovery objectives under the design-level ground motion for buildings, accounting for occupancy and importance to community function. The report also discusses several possible implementation strategies, from mandatory to incentivized voluntary adoption.

Following from these substantial developments from NIST and FEMA, California also pursued the direction of more resilient design for functional recovery. The California Assembly introduced legislation in early 2021 (California Legislature AB-1329, 2021) to require the next edition of the California Building Code to "*require buildings to be designed and built to a functional recovery standard for earthquake loads.*"

QUANTITATIVE ASSESSMENTS OF POST-EARTHQUAKE BUILDING FUNCTION

Despite recent policy initiatives, there is significant uncertainty regarding the analytical quantification of building functional recovery. This section reviews existing data and methods.

Data on Post-Earthquake Building Function from Past Earthquakes

There are limited empirical data on post-earthquake building function. Among the data that has been collected, Comerio & Blecher (2010) investigated reported downtimes from around 5,000 red- and yellow-tagged wood residential buildings that were damaged by the Northridge and Loma Prieta (CA) Earthquakes. On average, it took about two years to full repairs for these buildings; the data did not report times for regaining building function or reoccupancy.

Likewise, Eguchi & Chang (1996) surveyed owners and tenants of damaged buildings one year after the Northridge Earthquake. From the 61 survey responses, the authors showed that 9% of buildings with minor damage, and 50% of buildings with moderate damage experienced an initial loss of building function following the earthquake. Loss of building function was attributed to factors including structural damage, yellow tags, other hazards (e.g., asbestos), nonstructural damage, and damage to tenant contents. Some owners reported some partial level of building function during the repair.

Post-earthquake function of hospitals has garnered somewhat more attention. In their global review of hospital damage and function after previous earthquakes, Yavari et al. (2010) reported that, while structural damage was a major cause of loss of occupancy and function for hospitals constructed before major changes in design requirements (e.g., the 1972 California Hospital Seismic Safety Act), loss of function from nonstructural damage was significant in modern design. In particular, pipe failure and telecommunication issues were shown to affect the function of hospitals in the Northridge and Kocaeli (Turkey) Earthquakes, respectively; other types of damage affecting hospital function were loss of external power and water networks, failure of backup power systems, and damage to partitions, air conditioning, elevators, suspended ceilings, and medical equipment. Studying the Christchurch Earthquake, Jacques et al. (2014) found that much of the hospital function interruptions came from nonstructural damage and loss of lifeline services.

Mitrani-Reiser et al. (2012) documented the post-earthquake damage and function of hospitals after the 2010 Maule (Chile) Earthquake. Out of 135 hospitals in the affected region, many of which are similar in design and construction to U.S. hospitals, immediately after the earthquake four were not reoccupiable, 12 had more than 75% of the floor area impacted by earthquake damage, and seven had some area (<75%) impacted; these seven hospitals were studied in more detail to relate damage with building function. These hospitals had no significant safety issues or structural damage. However, nonstructural damage hindered function; damaged elevators impeded patient transport, collapsed ceilings and damaged heavy concrete-clad walls hindered the use of certain areas and patient rooms, damage to hospital equipment and some minor flooding shut down surgical rooms and other services, and damaged computers as well as storage shelves made some patient records inaccessible. As a result of this damage, there was significant loss of function for specialized operations such as dialysis and laboratory functions, whereas the emergency department was able to maintain function. While water distribution, electric power and telecommunications utilities were not in service after the earthquake, most of the hospitals were able to use back-up systems for water and power. However, none of the hospitals had back-up telecommunications, which significantly hindered the emergency response coordination. Most of these seven hospitals were back to a mostly-functional state within seven days after the earthquake.

Empirical and Judgment-Based Building Recovery Functions

To date, the most common method of assessing building recovery time, especially when evaluating the recovery of a community or region (e.g., Ceskavich & Sasani (2018); Lin & Wang (2017a; 2017b)), has been through the use of recovery functions, such as those from Hazus (FEMA, 2012b). Hazus defines building recovery times as a function of ground motion intensity, for a given building class, location, age, and height; Hazus times are based on a combination of engineering judgment and empirical evidence.

Kang et al. (2018) compared recovery functions from Hazus with permit and repair time data from 1,470 yellow- and red-tagged buildings from the 2014 Napa Valley (CA) Earthquake. The study categorized buildings into damage states based on post-earthquake inspection data, and used Hazus recovery functions to predict repair times for each inspected building. By comparing the predicted regional recovery with data from the earthquake. Kang et al. found the Hazus assessment of recovery time overpredicted the initial rate of community recovery and underpredicted the long-term rate of community recovery. Subsequently, Burton et al. (2019) used post-earthquake repair time data for wood frame houses from the 1989 Loma Prieta, 1994 Northridge, and 2014 Napa Valley Earthquakes to define empirical recovery functions that quantify the full repair time for single family dwellings.

Yavari et al. (2010) proposed a framework for assessing hospital function based on the documented damage of 218 facilities from five California earthquakes. The framework defined function based on the performance of four major systems found in hospital facilities: structural, nonstructural, lifeline, and personnel (i.e., post-earthquake availability of hospital employees). For each system, the authors defined four discrete performance levels, resulting in 256 possible combinations of system performance that describe the overall functional performance of the facility into one of four facility functional states: fully functional, functional (some sections of the facility are affected, but not fully disrupted), affected function (some sections of the facility are fully disrupted, but emergency services are still functional), not functional. Based on the description of damage to the facilities, the authors developed empirical relationships between ground motion intensity and the four performance states of each of the four facility systems.

Recovery Functions from Performance-Based Estimations of Repair Times

As an alternative to predefined recovery functions, building recovery can be assessed using a performance-based earthquake engineering (PBEE) framework to explicitly quantify the repair or functional recovery time of a structure, based on its specific characteristics. PBEE integrates a probabilistic hazard analysis, with a structural response assessment and a component-based damage assessment to quantify the damage to each component within the building for a given shaking intensity (Porter, 2003; Deierlein & Moehle, 2004).

FEMA P-58 is the most commonly used implementation of the PBEE methodology, and probabilistically quantifies a building's performance, based on its structural and nonstructural characteristics, in terms of repair costs, repair time, casualties, and unsafe placards (FEMA, 2012; 2018). Building repair times are quantified as an aggregation of the estimated time a worker takes to repair damage to each component within the building, based on a repair schedule that assumes workers either repair all floors simultaneously (parallel) or one floor at a time (series). FEMA P-58 suggests one worker is allocated to every 1,000 square feet of workspace. FEMA P-58 only quantifies building repair times, and does not consider the recovery of building function nor the impeding factors that delay the start of repairs.

Cimellaro and Piqué (2016) is one study that has used the FEMA P-58 framework to assess restoration of function, for hospitals. Restoration curves were defined assuming repairs to each floor occur in series, with function restored at each floor upon completion of the repairs at that level (i.e., repair completion time serves as a proxy for building function). They tracked repair times for each floor individually to quantify the partial functionality of the hospital, assuming that lower floors would be functional while repairs continued upstairs.

The Resilience-based Earthquake Design Initiative for the Next Generation of Buildings (REDi), extends the PBEE methodology to quantify building reoccupancy and functional recovery times (Almufti & Willford, 2013). This approach is implemented as a postprocess to a FEMA P-58 performance assessment. Building component damage states are put in "repair classes" to represent if damage to those components block building function or reoccupancy. Functional recovery or reoccupancy building recovery times are then estimated as the time to repair all components that are flagged as blocking function or reoccupancy, respectively, based on their average damage state. REDi also adds estimates of time for the pre-repair impeding factors, as well as a more sophisticated sequence for scheduling repairs (beyond the serial and parallel assumptions of FEMA P-58). The REDi method has been used in the performance-based design of new buildings, such as the 181 Fremont Tower in San Francisco (Almufti, et al., 2016), and as part of the U.S. Resiliency Council's seismic rating system (USRC, 2015).

Yet, there are several key areas where the 2013 published version of REDi oversimplifies the quantification of functional recovery, hindering its adoption for functional recovery policy initiatives. Among these, in REDi, the building's functional recovery performance is based on a "worst-case-component" architecture, meaning that, if any one component that affects function is damaged, the entire building is assessed as nonfunctional, potentially triggering hundreds of days of pre-repair impeding factors. In its current form, REDi is not set up to incorporate occupancy-specific requirements to function. Additionally, REDi was designed as post-process to FEMA P-58 computational tool PACT, hindering the statistical robustness achieved from REDi due to limitations in available metadata. After the 2013 publication of REDi, the primary authors have made some ongoing improvements to the REDi method (Paul et al., 2018), which are said to address some of these limitations, but the details of those developments have not been made public.

Burton et al. (2015) presented a method that extends the PBEE framework to quantify recovery times for residential buildings with application to community recovery. The method defines five limit states that quantify building performance (inspection required, loss of building function, loss of occupancy, irreparable damage, and collapse), which are aggregated over a region's building inventory to quantify community-level performance. In the study, the authors quantify the housing recovery for a hypothetical community by defining the loss of occupancy at the building level using a residual collapse capacity assessment. Conceptually, the authors suggest that the loss of function for each building could be determined through a FEMA P-58 or other damage assessment, but they do not define a specific method to do so.

Recovery Functions from Fault Tree Analysis

Fault trees are a failure analysis tools that map the operations of systems into discrete failure events (Fussell et al., 1974). Porter & Ramer (2012) outlined a framework to apply fault trees to assess building function, accounting for dependencies among building systems and their effect on function, applying it to post-earthquake function of a data center. The framework used assembly-based vulnerability approaches through PBEE to determine the damage to each component in the building. For a data center, the authors developed a fault tree to explicitly define how each component in the building, and its damage, affect building-level function. Mieler et al. (2015) also conceptualizes the use of fault trees to define building function.

Jacques et al. (2014) developed fault trees to explore building function of hospitals after the Christchurch Earthquake. In their framework, hospital function depends (probabilistically) on damage to essential hospital supplies and equipment, post-earthquake availability of personnel, damage to interior spaces, availability of support infrastructure (power, water, etc.), and integrity of building egress. Using empirical data from the earthquake to deterministically define the structural damage, nonstructural damage, backup systems, lifelines, and staff disruptions as inputs to the fault tree model, the authors showed that the framework had mixed success at capturing post-earthquake hospital function. For example, the framework accurately predicted the loss of function of out-patient services for all four hospitals, but overestimated the consequences of loss of backup power because personnel were able to situationally adjust and maintain certain functions; these interactions were not represented in the framework.

To define building functional recovery times in a performance-based framework, Terzic and Villanueva (2021) define story- and building-level damage thresholds for various components and component-groups; if the fraction of damaged components is greater than the damage threshold, the damage is assumed to compromise building function based on a series of subsystem fault trees. They provide an example application to a 13-story building (Terzic and Villanueva, 2021) and a 42-story building (Terzic and Kolozvari, 2020), but do not document all the assumptions needed to do the assessment for other types of buildings. They use the repair schedule model proposed by Yoo (2016), which incorporates critical path concepts to calculate repair times based on repair sequences and resource constraints. The Yoo (2016) model was informed by interviews with eight contractors in the southern California region and provides example crew allocations and repair sequence constraints for several archetypal steel frame buildings.

EXTERNAL FACTORS AFFECTING BUILDING RECOVERY

In addition to loss of function caused by damage to the building itself, indirect and external factors can significantly delay the start of repairs and impact the building's functional recovery. These impeding factors depend on the local surge in demand for trades and materials depending on the size of the earthquake (Dhalhamer and Tierney 1998). Comerio (2006) identified impeding factors including financing, economic and regulatory uncertainty, and construction delays. Aghababaei et al. (2020) used empirical data from tornado damaged buildings to show that delays related to inspections, financing, contractor and permitting are particularly significant. REDi outlines impeding factors that define construction delays from inspection, engineering mobilization, permitting, contractor mobilization, and financing (Almufti & Willford, 2013). Median REDi impeding times range from 5 days for inspection to around 50 weeks for some contractor, design, and finance delays, defined for a ground shaking intensity with a 475-year return period at a high seismic site.

It is well documented that the recovery of lifeline systems, including water, wastewater, electric power, natural gas and telecommunications are essential to the recovery of building function (e.g., Dhalhamer and Tierney 1998). A number of studies that have either conceptualized, defined, or provided frameworks to assess lifeline recovery (e.g., FEMA 2012b; Miles et al. 2018; Davis, 2019; Masoomi et al., 2020). However, incorporating these networks, and the related availability of key utilities, into the assessment of functional recovery of an individual building is complicated because network topologies, damage, and recovery are inherently region and earthquake dependent, while building function is ground motion and site dependent. To close the gap between building assessment and these network analyses, lifeline recovery functions provided in REDi (Almufti & Willford, 2013) range from three days on average for electrical network recovery to as much as 1-3 months of recovery for natural gas and water network recovery (for intensity with 475-year return period).

Characteristics of the human infrastructure and post-disaster decision making can also significantly impact building functional recovery (e.g., Marquis et al. 2017). The capacity of a business to recover and remain in operation depends on factors such as the size of the firm, the type of business, its financial condition, the ability of employees to get to work, the local economy, and the adoption of various business continuity strategies (Dhalhamer and Tierney 1998; Petak and Elahi 2001). Cremen et al. (2020) studied 22 businesses affected by the 2011 Christchurch Earthquake. Combining business-related factors with a PBEE assessment, they showed that, while building and lifeline damage was the most significant contributing factor to business interruption, many businesses were able to implement effective strategies to help recover business operations prior to the completion of building repairs. Likewise, household decisions to repair, rebuild, stay, sell, or relocate are functions of household characteristics such as income, ownership, time at current residence, and earthquake insurance, as well as community evacuations, and time spent in a temporary shelter (Burton et al. 2019).

SCOPE

Our goal is to develop a performance-based approach to quantify the capacity of an individual building to maintain and recover function, given the seismic damage to the building and its components, operationalizing the concept of functional recovery. The study develops methods to explicitly account for damage to the structural, architectural, mechanical, electrical, and plumbing systems in the building that contribute to loss of function. In doing so, we disaggregate building function characteristics and decision variables into their fundamental parts, thereby avoiding assumptions about function (e.g., that function is lost only if a building is red tagged) that hamper the utility of the functional recovery concept in supporting resilient design initiatives. The proposed method quantifies the performance of a building in terms of the three performance states: reoccupancy, building function, and full repair.

Our unit of analysis is an individual building and its constituent tenant units. A tenant unit is defined as a space within a building that serves a distinct purpose and may have different requirements to function from other spaces within the building due to its specific use case. Buildings can be made up of one or many tenant units. Because we focus on buildings, not businesses or households, external factors, such as household decisions and business continuity plans, are not considered. In addition, external lifelines and their impacts on functional recovery are excluded. This approach is taken because, beyond backup systems, the mitigation of the effects of lifeline disruption is typically outside the purview of the building designer.

OVERVIEW OF PROPOSED PERFORMACE-BASED METHOD

The proposed method probabilistically quantifies the building performance state at any time after an earthquake, estimating the recovery time to building reoccupancy, function, and full repair. In doing so, it builds on the performance-based computational architecture of FEMA P-58 (FEMA 2012; 2018) for the hazard assessment, structural analysis, and damage assessment. The simulated damage to a building's components is used to explicitly quantify the performance of various systems within the building. A building's performance state accounts for the impacts of each of these systems on building reoccupancy and function.

Our general approach for assessing a building's performance state is illustrated in Figure 2, and is structured according to the following logic. For a building or tenant unit to be reoocupiable, it must be safe to enter, each story of the building must be accessible, i.e., having appropriate egress, and tenant units must be safe from local falling and other safety hazards. For a building or tenant unit to be functional, the building and tenant unit must first be reoccupiable and tenants in the unit must be able to use the space for its basic intended purpose. Thus, in Stage 1, Building Safety, the building is checked for occupant safety hazards that would cause the whole building to fail reoccupancy, such as a red tag or extensive exterior falling hazards. In Stage 2, Story Access, each story is checked 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 each tenant unit. Building Safety, Story Access and Tenant Safety are required for *reoccupancy* of a particular space. Finally, Stage 4, Tenant Function, checks whether building systems are in a condition such that the tenants can function in the space, according to tenant and occupancy-specific requirements. The *full repair* performance state is reached when all repairs have been completed.

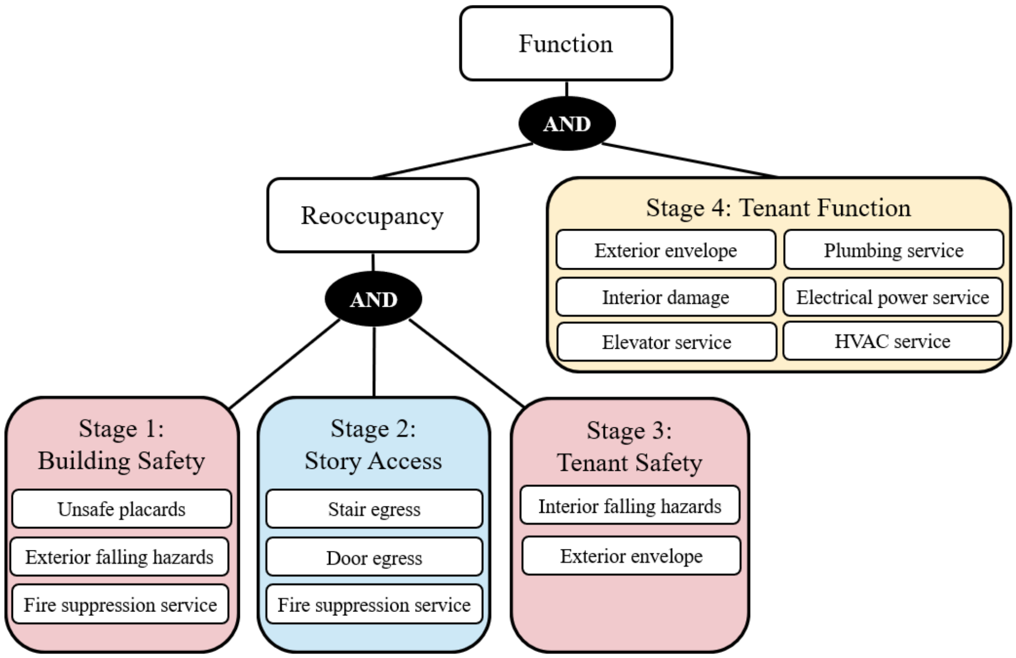

Figure 2. Illustration of the proposed building function module for assessing building reoccupancy and function.

In each stage, component damage is related to system-level function, based on a series of fault trees following, e.g., Porter and Ramer (2015) and Jacques et al. (2014). These fault trees are used to define the effect that component damage has on nine different building systems' damage and operation. Table 1 lists the relevant building systems. The function of each tenant unit is determined based on how the performance of each system meets or fails to meet tenant-specific requirements. The building's performance state is aggregated from the functional performance of all the tenant units within the building; full repair is quantified only at the building level. These calculations propagate uncertainties through Monte Carlo simulation, considering uncertainties in structural response, damage, and impeding and repair times.

The next sections of the paper define the logic and assumptions used in the proposed method to assess a building's performance state at any point in time after an earthquake. It also develops and describes a repair scheduling algorithm and method of quantifying impeding factors, which are used to assess how the function in the building is restored over time after the earthquake. Figure 3 illustrates the input/output structure and logical connections between the building performance assessment (Building Function Module) and repair schedule algorithm (Recovery Time Module)**Error! Reference source not found.**. A Matlab codebase that can be used to conduct this assessment and underlying data tables are available for download in the PBEE-Recovery Github repository (Cook, 2021a); the logic presented in this paper is consistent with v1.1.0 of the code.

Table 1. Building systems defined and stages of the assessment they affect.

System	Assessment stage	System components
Structural	Building Safety Tenant Safety Tenant Function	Columns, beams, walls, braces, slabs, etc.
Exterior Enclosure	Building Safety Tenant Safety Tenant Function	Exterior walls, precast cladding, glazing, storefronts, etc.
Interior Spaces	Tenant Safety Tenant Function	Interior walls, ceilings, slabs, lighting, flooring, tenant contents etc.
Stairs and Doors	Story Access	Staircases and doors
Elevators	Tenant Function	Elevators
Water/Plumbing	Tenant Function	Piping and bracing
Electrical/Power	Tenant Function	Electrical equipment
Heating Ventilation and Air Conditioning (HVAC)	Tenant Function	Equipment, ducts, piping, drop-downs, and fans
Fire Suppression	Building Safety Story Access	Piping, sprinklers, and bracing

REQUIRED INFORMATION

The building information required to assess the post-earthquake building performance state is the same as that needed for a typical FEMA P-58 assessment, including site seismic hazard information, estimations of structural response, and an inventory of structural and nonstructural components in each story and direction. Additionally, to quantify a building's performance state, information is needed about each tenant unit in the building, including its occupancy (e.g., residential, office), location, and inventory of structural and nonstructural components. For mechanical and electrical systems, it is necessary to define not only where the system's components are located, but also which areas of the building they service.

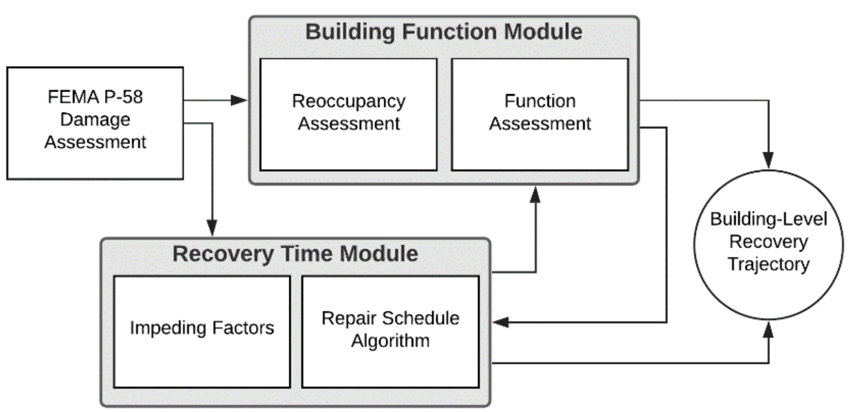

Figure 3. Illustration of the function and recovery time modules and integration with FEMA P-58.

Tenant Requirements

To function within a space, each of the building's tenants may have a unique set of requirements of the building's services and/or tolerance for damage, based on the tenant's specific operations. However, it is expected that similar types of tenants, with a shared occupancy type, may have similar functional needs. Therefore, Table 2 provides a sample set of tenant requirements for office and residential occupancies. The proposed method is intended to provide easily modifiable thresholds if other requirements are considered. For example, HVAC systems may not be needed in all climates, especially if units have passive ventilation systems to maintain airflow.

Table 2. Example requirements for building systems for Tenant Function for two occupancies

<table>
<tr><th>System</th><th>Performance Metric</th><th>Office</th><th>Residential</th></tr>
<tr><td>Exterior Enclosure</td><td>Percent of the perimeter area boarded up or severely damage</td><td>< 50% perimeter affected</td><td>< 75% perimeter affected</td></tr>
<tr><td>Interior Spaces</td><td>Percent of the interior area with falling hazard or severe damage</td><td>< 25% of the interior area affected</td><td>< 50% of the interior area affected</td></tr>
<tr><td>Elevators</td><td>Percent of functioning elevators</td><td>Units above the 3rd story need at least one operating elevator per 1000 occupants[1]</td><td>Units above the 5th story need at least one operating elevator per 1000 occupants[1]</td></tr>
<tr><td>Plumbing</td><td rowspan="3">Level of service provided</td><td colspan="2" rowspan="3">System operational in unit</td></tr>
<tr><td>Electrical</td></tr>
<tr><td>HVAC</td></tr>
</table>

[1] Elevator requirements are taken as one-quarter the typical design requirements for new design (which suggests one elevator per 250 occupants); the method assumes that in a post-earthquake setting, a less-than-ideal number of elevators would meet basic requirements for function.

Damage State Attributes

To relate the consequences of component-level damage to the fault trees presented in this method, we define additional damage state attributes for each component in the FEMA P-58 database. For example, the proposed attributes specifically identify which components and damage states affect interior function, create falling hazards, or are required for MEP operation, among others, and which do not. A complete list of all attributes defined in this method is provided in Table S1 of the electronic supplement; attribute assignments for each component damage state of the FEMA P-58 fragility database (2012; 2018) is provided in the companion code repository (Cook, 2021a).

BUILDING SAFETY

In Stage 1 (Figure 2), safety is checked on the building level. This check identifies several types of damage that indicate an entire building is unsafe, including structural safety concerns, safe egress, and risk of fire. The effect that each of these hazards has on the assessment of Building Safety is quantified using the fault tree shown in Figure 4. If any of these hazards are determined to exist based on the damage to each system, the building is designated as unsafe, and all tenant units within the building are not occupiable nor functional.

Unsafe Placards

Structural safety threats, encompassing both concerns of inadequate capacity to withstand aftershocks and loss of gravity load capacity, are present if the assessment identifies that an unsafe placard (red tag) would be posted on the building. An unsafe placard prevents reoccupancy. Unsafe placards are identified using a virtual inspection process, described in Cook et al. (2021b), which has been verified against data from the Northridge Earthquake. The virtual inspector attempts to mimic the post-earthquake inspection process and assigns unsafe placards based on the severity of component damage (Safety Class attribute) and the extent of damage within each structural system. The virtual unsafe placard identifies only structural safety concerns; other Building Safety issues are identified by other branches of the fault tree.

Safe Entry and Exit

Falling hazards on the outside of the building pose a risk to occupant egress and pedestrians. External falling hazards come from dislodged cladding, broken glass, severely damaged chimneys, roof tiles, masonry parapets, and so forth (ATC, 1989; 2005). The External Falling Hazard attribute (electronic supplement Table S1) identifies the component damage states that trigger external falling hazards event in the fault tree in Figure 4. External falling hazards are only treated as a safety concern if they cause a building entrance or exit to become blocked or unsafe. An entrance or exit door becomes unsafe if there is a falling hazard anywhere above the door access zone, where the door access zone is defined as three times the width of the door. Entrance or exit doors, racked by residual lateral displacement demands, can also cause the door to become inaccessible/unsafe, and compromise safe building egress.

If enough entrance doors are damaged or considered unsafe for access on the first story, the whole building is deemed unsafe. The method assumes that there needs to be at least 50% of the required design egress (International Code Council, 2009) for a building to be safe to access in a post-earthquake setting. We justify acceptance of fewer egress routes than required by design because these requirements would likely be relaxed after the earthquake to support building reoccupancy (FEMA, 2019). However, if the fire suppression system is not operational, we assume egress requirements would be more stringent. Therefore, the egress requirement tightens to at least 75% of design egress when a fire suppression system is not installed or is damaged. The consequence of external falling hazards on building safety can be mitigated prior to their full repair through a temporary repair measure, e.g., by boarding up broken windows and glazing; temporary repair measures are discussed later in detail.

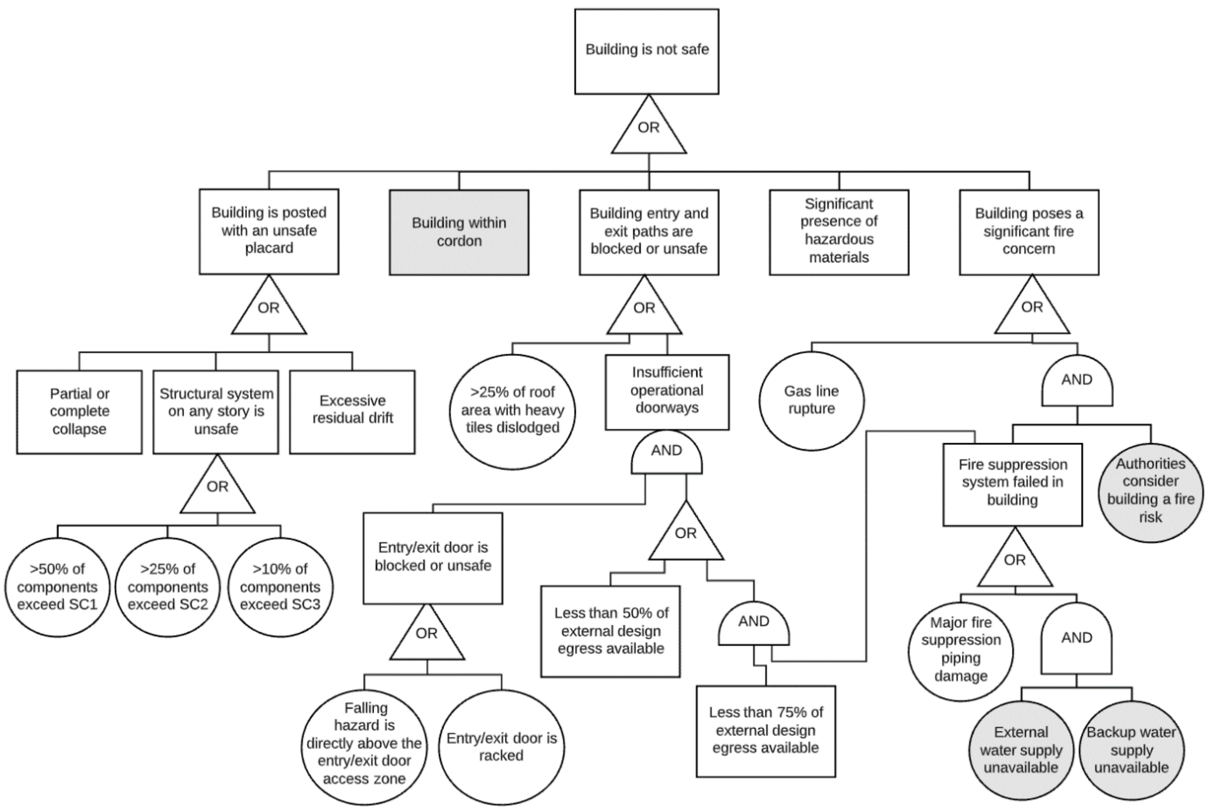

Figure 4. Fault tree determining Building Safety (Stage 1). Gray events are not currently considered. Safety Classes (SC) used in defining the unsafe placarding are defined Cook et al. (2021b).

Fire Safety and Fire Suppression

Fire following an earthquake can pose a major risk to occupant safety; in the Northridge Earthquake, for example, there were 110 earthquake-related fires, mostly fueled by broken gas lines (NIST, 1999). Given this risk, the failure of a gas line in or near the building would likely result in the closure of the building until the gas line could be repaired or shut off (ATC, 1989; 2005). Gas line rupture can be assessed through the fragility functions from Lanzano et al. (2013), where Risk States 1 and 2 trigger the hazardous material fault tree event (Figure 4).

The condition of the fire suppression systems is also relevant to Building Safety and reoccupancy. FEMA P-2055 (FEMA, 2019) provides guidelines on post-disaster habitability requirements, noting that the failure of the fire suppression system by itself should not hinder reoccupancy of a building, as long as a fire watch is in place and the fire suppression system is restored within 30 days after the earthquake. Therefore, in the proposed method, failure of the fire suppression system (assessed through the fault tree in Figure 4) only results in the closure of the building if the building officials or fire marshals consider the building to be a fire risk.

Other Building Safety Concerns

Other types of damage may also cause a building to become unsafe, such as cordons from nearby buildings, which caused extensive closures after the 2011 Christchurch Earthquake (Mieler et al., 2016; Hulsey et al. 2018; Deierlein et al. 2020), or the presence of hazardous materials, such as asbestos wall boards and ceiling tiles, which created reoccupancy issues after the 1994 Northridge Earthquake (ATC, 2000). Cordons are not currently considered in this study as they are outside the scope of the individual building-level assessment. The Global and Local Hazardous Materials attributes (electronic supplement Table S1) identifies the component damage states that trigger global or local hazardous material events in the Building Safety fault tree, respectively; global hazards affect the safety of the entire building, while local hazards only affect the tenant unit where the hazard is located.

STORY ACCESS

In Stage 2 of the proposed method (Figure 2), each story is checked for accessibility and egress according to the fault tree in Figure 5**Error! Reference source not found.**. The accessibility of each story is based on the number of functioning stairways and stairwell doors at each story. If a sufficient number of doorways or stairwells are severely damaged, the story is considered inaccessible. Each story is checked separately, and access impedes all tenant units at that level. Likewise, if there is sufficient damage to the stairs on a particular story, that story, the story immediately below, and all stories above would become inaccessible, while the stories below maintain access.

In the proposed method, only severe damage that impedes the use of stairs and doors affects access and egress, as identified by the Affects Access attribute (electronic supplement Table S1). For stair components in the FEMA P-58 (2012; 2018) database, damage is usually classified into three damages states involving: aesthetic damage, minor structural damage not affecting live-load carrying capacity, and severe structural damage affecting the staircase's live-load carrying capacity. In the proposed method, the latter two damage states are flagged as affecting access because of visual concerns that would be present for either damage state. Likewise, door fragilities typically have two damages states (FEMA 2012; 2018). Both damage states are associated with door racking and thereby assumed to impede access.

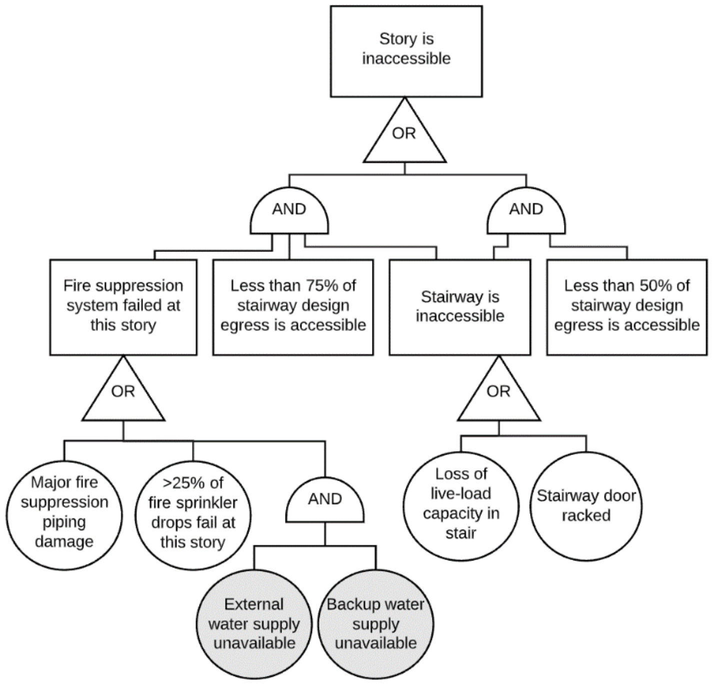

Figure 5. Fault tree defining Story Access (Stage 2). Gray events are not currently considered.

We assume that stair and door damage only affects access if sufficient egress is not maintained**Error! Reference source not found.**. To maintain access of a given story, the proposed method assumes that at least 50% of the required design egress needs to be maintained; we require at least 75% of design egress when the fire suppression system at a story is not installed or properly operating. The effect of door racking on story access can be mitigated prior to a full repair of the door, by simply unjamming the racked door as a temporary repair; we consider no temporary repair measure for severe stair damage, which is assumed to require a specialized design and repair.

TENANT SAFETY

If the proposed method finds the building is safe and the story is accessible (Figure 2), each tenant unit is checked for local safety hazards using the fault tree in Figure 6. These local safety hazards pose a risk to the occupants in some areas of the building but are not extensive enough to be caught in the Building Safety stage. Local safety hazards identified here are severe exterior enclosure damage, interior falling hazards from structural components, nonstructural components, and tenant contents, and the local presence of hazardous materials.

In this method, damage that compromises the safety of the exterior envelope occurs when more than 10% of the tenant unit perimeter area is severely damage, as identified by the Damages Envelope Seal attribute (electronic supplement Table S1). This damage is presumed to result in large openings in the side of the building, such as precast cladding anchorage failure, and broken and fallen glass in curtains walls, which compromises the integrity of the exterior envelope causing the tenant unit to become unsafe (FEMA, 2019). The effect of severe exterior envelope damage on tenant safety can be mitigated prior to a full repair by boarding up the damaged panels as a temporary repair (FEMA, 2019).

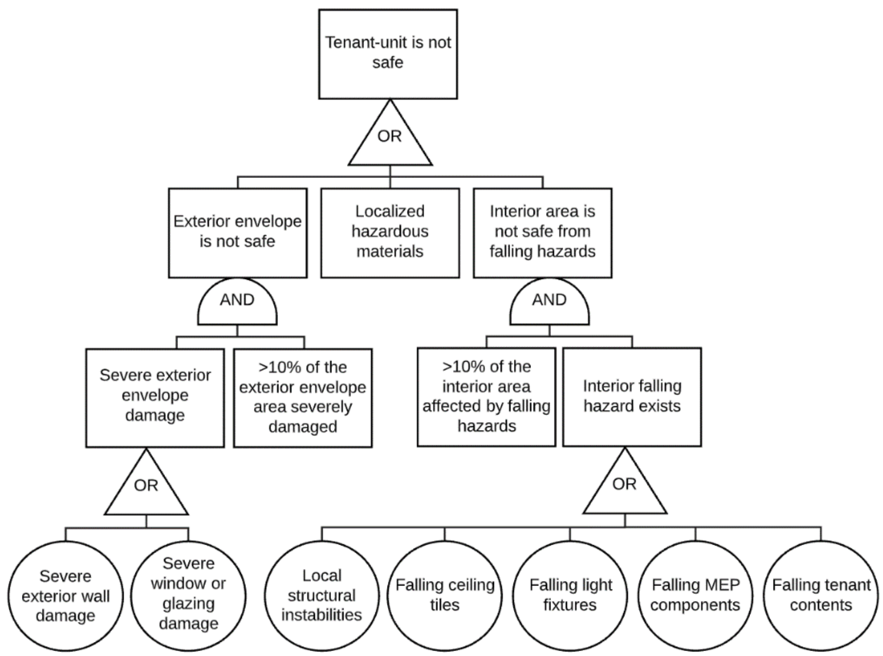

Figure 6. Fault tree defining Tenant (Local) Safety (Stage 3).

Interior falling hazards, caused by damage to a variety of interior components, can cause the tenant unit to become unsafe to occupy (Jacques et al., 2014). Currently, the method suggests that if more than 10% of the interior area of the tenant unit is affected by interior local falling hazards, the tenant unit is unsafe to occupy. If 10% or less of the interior area of the tenant unit is affected by interior falling hazards, we assume the local falling hazards can be sectioned off and basic function resumed in the space (provided other requirements are met).

Components damage states that trigger local falling hazard concerns, such as moderate or major damage to suspended ceilings, is identified by the Interior Falling Hazards attribute (electronic supplement Table S1). Each component that poses a falling hazard is also assigned a specific area (in plan) that is affected by that falling hazard; the total area within the tenant unit affected by falling hazards is calculated based on the location and affected of each damaged component within the tenant unit. If the locations of each component within the tenant unit are not explicitly modeled, simplifying assumptions can be made to estimate the affected area (Cook et al., 2021b). To do so, affected areas of the same type of components can be summed since the components are unlikely to occupy the same space. However, components of different types may or may not occupy the same space within the tenant unit and can be combined by taking the square root sum of squares of the affected areas. The assigned affected areas for each component are mostly adopted from the falling hazard casualty logic of FEMA P-58 (2012; 2018). Many of the interior falling hazards effect on function can be mitigated prior to a full repair by removing and bracing components as a temporary repair measure.

ASSESSMENT OF BUILDING FUNCTION

In Stage 4 (Figure 2), each tenant unit in the building is checked against a set of tenant-specific requirements to determine if any system is hindering function in that unit. This stage involves quantifying the extent of damage to and level of service provided by each system in Table 1, then comparing the performance of each system against a set of tenant-specific requirements to determine if function is affected. If the requirements for reoccupancy are met and the performance of each system satisfies the tenant requirements, the tenant unit is functional. An example set of tenant requirements is provided in Table 2.

BUILDING ENVELOPE

The exterior enclosure of a building, or building envelope, establishes the definition of interior vs. exterior space; significant damage to the building envelope leaves building occupants less protected from external elements, the building susceptible to water damage, and potentially reduces interior natural light due to temporary repair measures. We define the effect that building envelope damage has on tenant function in the fault tree provided in Figure 7**Error! Reference source not found.**.

Damage to the roof that severely compromises the roof structure or weather seal, prohibits function in the space below. For a multi-story building, we assume that a compromised roof only affects the function of the tenant units in the top floor. Component damage that severely compromises the roof's structure includes punching of the roof slab and failure of flexible roof diaphragms; if over 10% of the roof area (in plan) undergoes this type of damage, the roof is flagged as compromised. Likewise, we assume severe roof tile damage to over 25% of the roof area compromises the weatherproofing of the roof.

Severe cladding damage can also compromise the building's envelope seal. If the extent of exterior enclosure damage, quantified as the percent of the tenant unit's cladding area (in elevation) with severe cladding damage, does not satisfy the tenant functional requirements, the tenant unit is no longer functional. Cladding and roof component damage states that affect the envelope seal are assigned based on the Damages Envelope Seal attribute (electronic supplement Table S1); minor damage such as cracked windows have no effect on function. The default tenant requirements (Table 2) assume that function is possible with a much higher extent of cladding damage compared with the Tenant Safety check of exterior components in Stage 3 (10% of the perimeter area). However, temporary repairs to the exterior enclosure system (securing walls and boarding up windows) are assumed to block interior natural light and therefore mitigate their effect on tenant function.

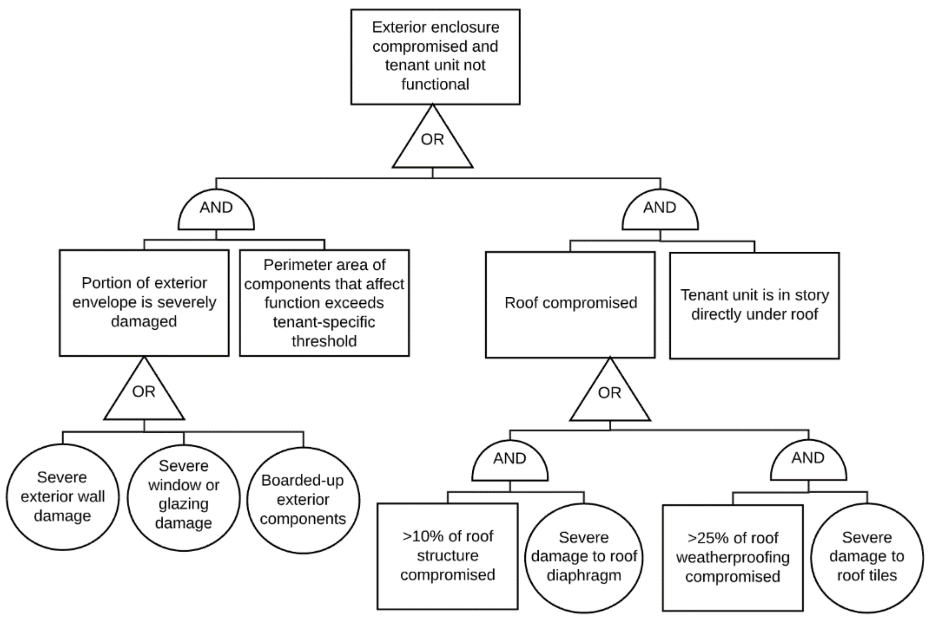

Figure 7. Fault tree defining the performance of the exterior enclosure for Tenant Function (Stage 4).

INTERIOR SPACE

The presence of interior falling hazards, severely damaged floors, ceilings, or walls, or scattered tenant contents may cause the interior space of a building to not be functional for tenant use (Yavari et al. 2010; Mitrani-Reiser et al., 2012; Jacques et al., 2014). While some isolated severe interior damage would likely not impact tenant function, extensive damage throughout a space could cause the entire tenant unit to become nonfunctional, depending on the tenant's tolerance for interior damage. In the proposed method, interior damage that affects building function is associated with severe damage that either creates an interior falling hazard or causes the space to be unusable, and is checked using the fault tree provided in Figure S1 of the electronic supplement.

Wall damage only affects interior function for very severe damage states where studs have buckled, and sheathing has separated; pipe failures can also lead to flooding of interior spaces, but is not currently considered. The Obstructs Interior Space attribute (electronic supplement Table S1) identifies each interior nonstructural and structural component damage state that has the potential to impede interior function; we also identify the floor area (in plan) affected for each component's damage. The total affected area within a tenant unit is quantified by combining the area of all affected interior components, based on their location within the tenant unit. If specific component locations are unknown, an estimate of the total affected area can be developed (Cook, 2021b). If the extent of interior damage is beyond the tenant requirements, the tenant unit is no longer functional. Many of the damage states that impede the use of the interior space are assigned temporary repair measures to mitigate their effect on tenant function prior to their completion of the full repair, as discussed later in this paper.

ELEVATORS

While not all buildings and tenant units need elevators to function, some people and activities, e.g., occupants in high-rise buildings and patient transport, are impacted by elevator operations. Here, this impact is quantified with the fault tree in Figure 8**Error! Reference source not found.**. Elevator operation is based on damage to the elevators' components, damage to the motor control center, and loss of electrical power (either due to damage to the building system or loss of external power supply). Most of the elevator and motor control center damage states cause the elevators to be not operational, as identified by the Impairs System Operation attribute (electronic supplement Table S1). Elevator failures are modeled independently from other elevators; however, failure of the motor control center or loss of the power supply causes loss of operation of all elevators in a building. Fault trees governing the operation of the electrical system and power supply are discussed later. As most large buildings are designed with multiple elevators to reduce waiting times, in a post-earthquake setting, not every elevator is required for function, as suggested by the example Tenant Requirements provided in Table 2.

POTABLE AND SANITARY WASTE PLUMBING SYSTEM

Water and wastewater systems in buildings are essential to occupant health and tenant function; while temporary services could provide short term solutions to shelter, many occupancies, such as hospitals, residence, and offices, need steady water supply for basic function (FEMA, 2019). Here, the performance of the plumbing system is quantified based on the fault tree provided in Figure S2 of the electronic supplement**Error! Reference source not found.**. Plumbing system operation depends on damage to the potable water and sanitary waste piping components, and the external water supply. The piping components include both large diameter piping (distribution mains) and small diameter piping (branches); major damage to a main supply pipe disrupts the plumbing services to the entire building, where major damage to a smaller branch pipe only disrupts service to the tenant unit that pipe is serving. Component damage that affects the operation of the plumbing system is identified by the Impairs System Operation attribute (electronic supplement Table S1).

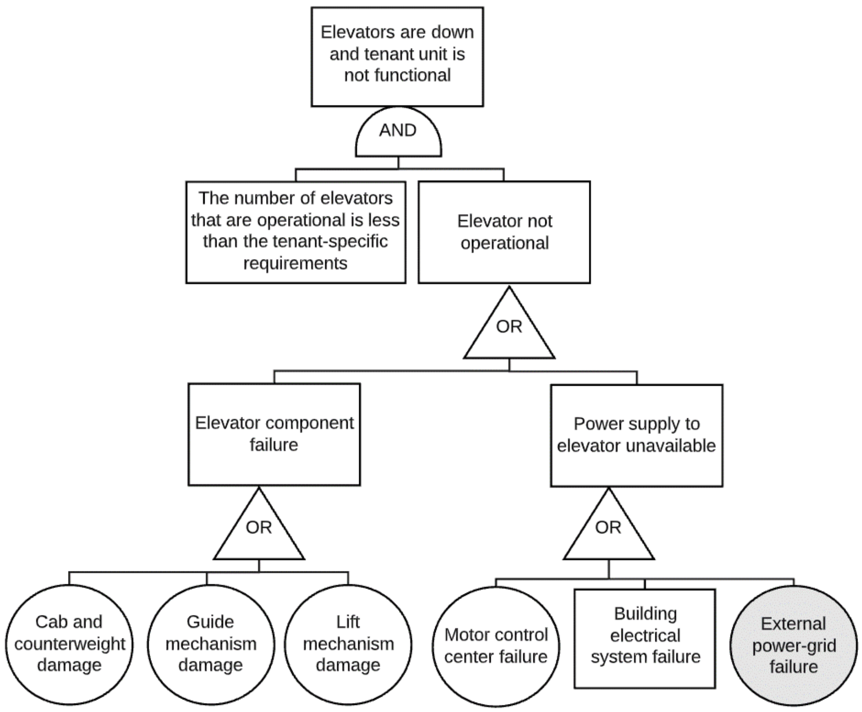

Figure 8. Fault tree defining the performance of the elevators for Tenant Function (Stage 4). Gray events are not currently considered.

ELECTRICAL POWER SYSTEM

Many functions of modern society depend on electrical power to operate, such as food storage, lighting, internet connection, etc., and failure of the electrical power system would likely severely hinder the ability for most occupancies to function. Electrical system operation depends on damage to the electrical equipment, including the transformers, switchgears, and distribution panels, and the external power supply, as defined by the fault tree in Figure 9.

Major damage to the transformer or switchgear would disrupt the electrical service for the entire building, whereas major damage to a distribution panel would only disrupt service to the tenant unit where the panel is located. Some buildings, such as hospitals, have backup systems to mitigate the loss of external electrical power supply. When these systems are present, we assume that any major damage to the backup system equipment fails the backup power supply for the entire structure. Component damage that affects the operation of the electrical system is identified by the Impairs System Operation attribute (electronic supplement Table S1).

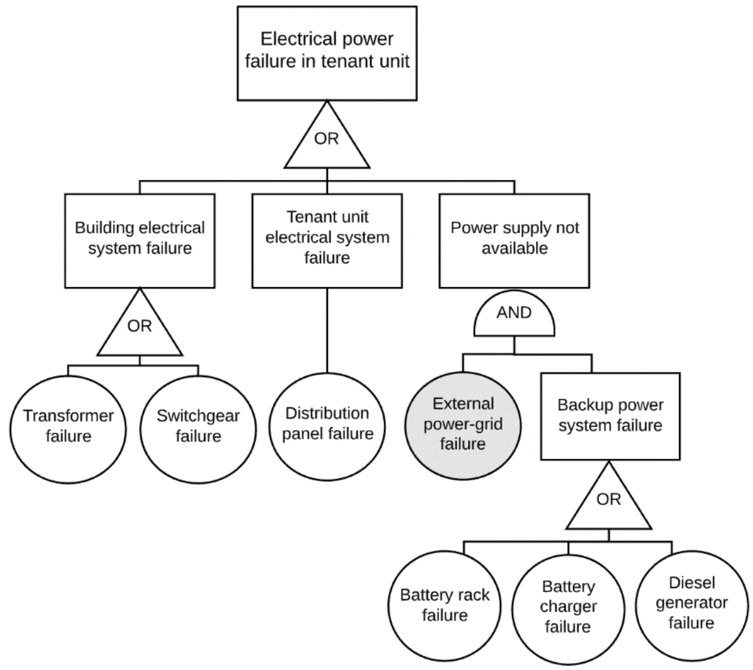

Figure 9. Fault tree defining the performance of the electrical system for Tenant Function (Stage 4). Gray events are not currently considered.

HEATING VENTILATION AND AIR CONDITIONING SYSTEM

The operation of the HVAC system is dependent on heating and cooling system equipment, exhaust and fan equipment, air distribution, chilled and heated water distribution, the electrical power supply, and depending on the system, the supply of natural gas. The configuration of the HVAC system typically depends on the age, size, and type of building. In this method, we construct fault trees for several typical HVAC system configurations common to modern U.S construction. Typical HVAC system configurations are provided for large multi-story, large single-story, and small structures; fault trees defining the operation and failure events for each of the HVAC configurations is provided in figures S3 through S7 in the electronic supplement.

For each component in the HVAC system, we identify the damage states that affect the operation of the HVAC system using Impairs System Operation attribute (electronic supplement Table S1). Not all component failures affect the operation of the HVAC system equally. For example, in large structures, the chillers and cooling towers provide chilled water (for air cooling) for the entire building, and the failure of these components can lead to loss of HVAC operation for the entire building. However, air handling units, distribution ducts and variable air volume (VAV) often serve specific sections of the building; the consequence of failure for these components may only lead to local loss of HVAC operation. Additionally, some HVAC equipment components are designed to operate in parallel, such as chillers and cooling towers, such that some component failures can be withstood without system failure. For HVAC equipment that is designed with redundancy, we assume that the components are designed using the "n+1" rule, where the systems are designed with one additional unit beyond the required capacity, to accommodate maintenance and failure scenarios. For HVAC distribution components, such as ducts, drops, in-line fans, and variable air volume boxes, acceptable damage thresholds are provided for each HVAC distribution component due to their inherent redundancy within a given tenant unit (electronic supplement Table S2). The overall performance of the HVAC system in the tenant unit is aggregated from the component-level damage using the fault tree associated with the relevant HVAC system configuration.

QUANTIFYING RECOVERY TIME

A building's post-earthquake performance state and level of damage is not static; as each component and system is repaired, the building gradually, regains function. To estimate the time until damage is repaired and building function is restored, a realistic representation of the building's repair schedule is required. A building repair schedule determines when repairs of each system and its constituent components are conducted, and the factors impeding the initiation of repairs. This schedule is used to develop repair time estimates that are combined with the building function assessment to develop the recovery trajectories, as illustrated in Figure 1. Function can be gradually restored as temporary and other repairs are carried out.

The key novelties of our repair schedule include the definition of temporary repairs, which greatly influence time to reoccupy and restore function for buildings with low to moderate levels of damage, and the development of a repair schedule that prioritizes restoration of function. The repair schedule is determined on a realization-by-realization basis, and considers all damaged components, instead of just the components affecting function. In concept, other repair time methods could be used in conjunction with the assessment of building reoccupancy and function performance presented above, with the requirements that the repair time module tracks the start and stop of repairs for each individual building system.

IMPEDING FACTORS AND TEMPORARY REPAIRS

Impeding factors are those activities or factors that delay the onset of repair after an earthquake, and include building inspection, design and permitting, contractor mobilization, temporary clean-up and repairs, and other factors, as shown in Figure 10. The impeding factors considered here are inspired by previous work including Almufti and Willford (2013), Aghababaei et al. (2020), and Terzic and Kolozvari (2020), but are defined to ensure that they are compatible with the goal of assessing when function and reoccupancy can be restored under a range of shaking intensities. Financing, the design track (engineering mobilization, design, and permitting), and contractor mobilization are assumed to take place in parallel, and the times associated with each depend on the severity of the ground shaking and damage. The longest such sequence governs when repairs can begin for a given building system. The key difference here from previous impedance factor models is that this delay is calculated on a system-by-system basis; the longest such sequence governs when repairs can begin for a given building system. For example, if no design or permits are needed for electrical and plumbing repairs, those repair actions can take place before the design track is completed for other systems.

An overview of the types of impeding factors and temporary repairs considered in the method, their triggers, affected systems, and estimated median times are presented in the following sections. Some of the impeding factor times may be affected by a regional surge in demands for labor and materials associated with large earthquakes affecting a major region; while the time delay of regional demand surge is not quantified in this study, the factors that would likely be affected are indicated below.

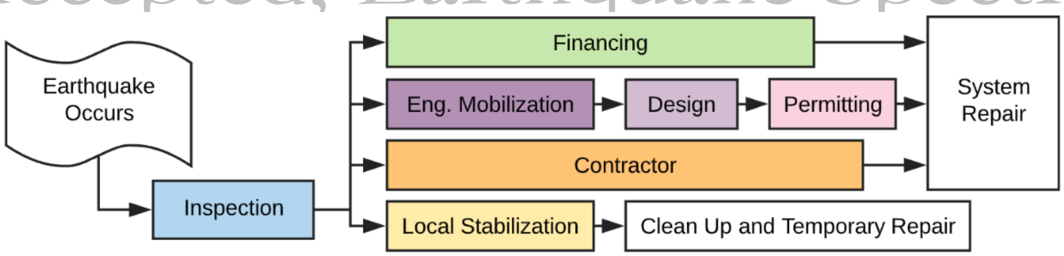

Figure 10. Flowchart factors illustrating the proposed impeding factors and schedule.

Clean up, Temporary and Local Stabilization Repairs

After an earthquake occurs, temporary repair actions, such as clean up, temporary and local stabilization repairs, can occur immediately after any needed inspections, and in parallel with other impeding factors. Clean up (e.g., picking up falling ceiling tiles) and simple temporary repairs (e.g., unjamming a door) are assumed to take three days (median). Longer temporary repairs include removing, securing, and barricading of exterior and interior falling hazards, as well as tarping or boarding up of broken windows and compromised cladding and are assumed to have median times of one to two weeks. Local stabilization, such as shoring, is assumed to take three weeks (median). Some damage, such as widespread structural damage or localized loss of gravity-load carrying capacity, cannot be temporarily repaired or cleaned up.

Local stabilization repairs are assumed to precede any other temporary repairs (which occur in parallel). While temporary repair actions can mitigate the effect that damage has on reoccupancy or function, they do not block the start of the full system repair or change the subsequent time required to repair damaged components. Therefore, temporary repair actions only trigger if they can be resolved prior to the completion of the full repair.

The various damage states that have temporary repair measures, require shoring, and their assumed median repair times are identified for each component using the proposed attributes in Table S1 in the electronic supplement; the median times for temporary repair actions are selected based on the judgement of the authors and are assumed to be inclusive of the time needed to find and mobilize a crew to conduct the temporary repair work.

Inspection

Inspection times are assumed to be three days for essential facilities and seven days for other buildings, as shown in Table 3. These values are based on the estimates of inspection time presented in Almufti and Willford (2013) and Terzic and Kolozvari (2020). A building inspection is triggered if damage to any structural system at any story reaches 50% of the limits defined for an unsafe placard. In practice, this means that any severe Safety Class 3 damage indicates an inspection is required, and most buildings with Safety Class 1 and 2 type damage need inspection. The inspection time can be reduced to 1 day with the introduction of a Building Occupancy Resumption Program (BORP) or equivalent.

Table 3 – Inspection impeding times.

Condition	System	Trigger	Median Impeding Time
Non-essential facility	Impedes all systems	50% of Red Tag threshold	1 week*
Essential facility			3 days*
BORP or equivalent			1 day

**Affected by demand surge factor if event damages a large region*

Financing

Financing is one of the three impeding activities that could begin concurrently after inspection. Financing time, summarized in Table 4, is required if the value of repairs needed exceeds the building owner's immediately available funds, or cash-on-hand (COH). Pre-arranged credit should be included in COH. The distinction between financing options is similar to the structure proposed by Almufti and Willford (2013); the provided median times are based on the judgment of the authors, informed by communications with an SBA loan specialist and private loan officers. Due to the long time taken to secure insurance payouts, the insurance impeding time model assumes that even owners with insurance will pursue private financing to conduct the repairs before the insurance payment is available.

Engineering Mobilization and Design

Engineering mobilization and design time is required for most structural repairs, as well as the repair of severe damage to stairs and exteriors. The component damage states requiring re-design are indicated in the code repository (Cook, 2021a) by the Requires Redesign attribute (electronic supplement Table S1). The assumed times include the time it takes to find an engineer and for them to gain familiarity with the project (engineering mobilization time), and for the design work to be completed enough to begin repairs (engineering design time). Engineering mobilization and design times are triggered independently for each system that requires redesign; the provided time estimates are based on the judgment of practicing engineers. The mobilization time is assumed to be 1 day if the owner has an engineer on retainer and 2 weeks otherwise (affected by a surge factor if the event affects a large region).

Table 4. Financing impeding times.

Condition	System	Trigger	Median Impeding Time
Insurance	All	RC > COH	Doesn't Control (see private loan time)
Private loans	All	RC > COH	60 days
SBA-backed loans	All	RC > COH	60 days*

**Affected by demand surge if event damages a large region*

The median time to complete engineering design work is assumed to be proportional to the total cost of the repairs and is estimated by the system design time defined in Equation 1.

$$SDT = \frac{RC_{total} \times f}{r \times t \times w} \quad (1)$$

Where SDT is the system design time in days, RC_{total} is the total repair cost from the FEMA P-58 analysis, f is the design fee ratio – estimated as 4% for repair projects, r is the engineering rate – estimated as \$175 per hour, t is a team factor accounting for parallel time spent on the project from other team members – estimated as 1.3, and w is average workday – estimated as 8 hours per day; the estimated values for calculated SDT are based on the judgment of structural engineers. For each system affected by engineering design impedance, maximum and minimum SDT values are provided in Table **5**. We assume that having an engineer on retainer only reduces engineering mobilization times and not engineering design time.

Table 5 – Engineering design times.

System	Trigger	Median Impeding Time	Min Time*	Max Time*
Structure	Triggered for this system if any system damage requires re-design	SDT	2 weeks	6 months
Stair	Triggered for this system if any system damage requires re-design	SDT	1 week	1 month

Exterior		SDT	1 week	3 months

**Bound on median time*

Permitting

Permitting is assumed to take place after engineering design is complete. Two levels of permits are considered (Table 6). Over-the-counter permits are for items that do not require significant review and are assumed to only take one day (median). Full review permits are for more heavily damaged systems that require complicated repair measures, such as damage to the significant structural, cladding, or stair damage and requires eight weeks (median). The type of permit required for each damage state is identified by the Permit Type attribute (electronic supplement Table S1). Both permit types block the start of repairs for any system that has damage requiring permitting. The values provided in for full review permits are similar to the estimates reported by Terzic and Kolozvari (2020) and Almufti and Willford (2013).

Table 6. Permitting times.

System	Trigger	Median Impeding Time
All systems needing permitting	Triggered if any system damage requires "over-the-counter" permitting	1 day
All systems needing permitting	Triggered if any system damage requires "full review" permitting	8 weeks*

**Affected by demand surge if event damages a large region*

Contractor Mobilization

Contractor mobilization times account for the time to arrange for general and/or sub-contractors to arrive on site. Contractor mobilization times are determined independently for each building system and are assumed to occur in parallel; a building with a greater number of damaged systems is anticipated to have greater overall impedance. The values provided in Table 7 generally range between the contractor mobilization estimates reported by Terzic and Kolozvari (2020) at the lower end, and Almufti and Willford (2013) at the upper end. Given the significant uncertainty in predicting contractor mobilization time, we assume that the time is uniformly distributed between the minimum and maximum time; users can replace these estimates if better estimates from contractors are available.

Table 7. Contractor mobilization times.

Condition	System	Trigger	Min Time*	Max Time*
No contractor on retainer	Structure	any system damage	4 weeks	12 months
	Stair	any system damage	2 weeks	6 months
	Exterior	any system damage	2 weeks	6 months
	All other systems	any system damage	5 days	2 months
Contractor on retainer	Structure	any system damage	1 week	6 months
	Stair	any system damage	5 days	3 months

	Exterior	any system damage	5 days	3 months
	All other systems	any system damage	1 day	1 month

**Affected by demand surge if event damages a large region*

REPAIR SCHEDULE

The proposed repair schedule algorithm translates component-level repair times from the FEMA P-58 (2012; 2018) database (i.e., worker days) to building-level repair times, taking into the consideration worker allocations, construction constraints, delays in the start or repairs, and owner priorities (2012; 2018). The repair schedule algorithm accounts for critical construction constraints and details, breaking down repairs by system and scheduling crews to each damaged building system, based on the assumed available workers and prioritization of repairs. The repair schedule presented here adopts much of the structure and worker assumptions from the repair schedule algorithm developed by Yoo (2016), with several modifications to repair constraints, prioritization, and optimization.

The repair schedules algorithm allocates crews of workers to repair to the damaged components, beginning with the highest priority unconstrained system at the first story. The number of workers assigned to each system is based on assumptions about the number of crews, crew sizes for different building systems/trades, and worker limits for both the floor and the building. If there are still workers available, the algorithm moves first to repair the most highly prioritized unconstrained system in other stories, repairing in parallel, and second to the most highly prioritized unconstrained system at that story. Workers are allocated to repairs until a construction constraint or maximum worker limit is reached. Additional crews and repairs must wait until there are enough available workers (i.e., room in the building) to begin repairs, representing bottleneck and float items in an actual repair schedule. Once workers finish with a system, more room becomes available for additional workers to be allocated to an un-repaired system until the building is fully repaired. Impeding factors may also constrain the start of system repairs; if workers are available, but a system is constrained by an impeding factor, workers will be allocated to the next highest priority unconstrained system.

Prioritization of Repairs for Recovery of Function

This repair schedule algorithm assumes that an owner and the repair team prioritize restoration of function where practical, meaning that actions that restore function are taken first unless there is some logical construction constraint (e.g., partition damage that affects function would be repaired before external aesthetic damage, but not before structural repairs on a given story, due to construction constraints). The algorithm begins with a default repair prioritization, provided in Table 8. In the assessment, this list is adjusted to prioritize functional recovery, per each realization; systems whose damage is not impairing function are moved down the list. Systems that are prioritized maintain their same relative priority with other systems that also affect function. Uncertainties in the prioritization scheme are not presently considered.

Table 8. Default prioritization of building systems in repair schedules. This list is updated based on which system(s)' damage affects function.

<table>
<tr><th>System ID</th><th>System</th><th>Default Repair Priority</th><th>Number of Damaged Units per Crew</th><th>Max. Number of Crews per Component Type</th></tr>
<tr><td>1</td><td>Structural</td><td>1</td><td>10</td><td>10</td></tr>
<tr><td>2</td><td>Exterior Enclosure</td><td>5</td><td>10</td><td>2</td></tr>
<tr><td>3</td><td>Interior Components</td><td>9</td><td rowspan="7">All</td><td rowspan="7">1</td></tr>
<tr><td>4</td><td>Stairs and Doors</td><td>2</td></tr>
<tr><td>5</td><td>Elevators</td><td>7</td></tr>
<tr><td>6</td><td>Water/Plumbing</td><td>3</td></tr>
<tr><td>7</td><td>Electrical/Power</td><td>4</td></tr>
<tr><td>8</td><td>HVAC</td><td>6</td></tr>
<tr><td>9</td><td>Fire Suppression</td><td>8</td></tr>
</table>

Worker Allocations

Worker crew sizes and allocations are based on primarily on Yoo (2016), who conducted interviews with a small number of contractors in California. These assumptions are reported in Table 8. For each building system, the required crew sizes for various components are determined based on the severity of component damage (quantified by the average damage state per story in a given realization), and the number of crews is based on the number of damaged components. The required crew sizes for each damage state are provided in data tables in the code repository. When assigning crews to repair system damage, the number of crews assigned fluctuate depending on worker limitations and construction constraints. However, the crew sizes for various types of damage remains constant.

Construction Constraints

The repair scheduling algorithm is limited by an assumed maximum number of workers at a given floor, maximum workers on site, maximum number of crews per system, and construction sequence constraints. Workers are limited to 1 worker per 1000 sq. ft. at any given story (FEMA 2012; 2018) and limited to 20 to 260 workers on the site, depending on the size of the building (REDi, 2013). The maximum number of crews per system are based on the example worker allocations provided by Yoo (2016). Besides the worker limits, there are no restrictions on how many stories can be repaired at once.

The repair scheduling algorithm additionally requires that interior finishes at a particular story are never repaired before structural components at the same story, even if the interior finishes are affecting function. Finally, if the structure is red tagged, the structural components must be repaired first, starting at the bottom story, until all the structural components are repaired for the whole building. Structural repairs among multiple stories can occur in parallel, as long as worker limitations are satisfied (Figure 11).

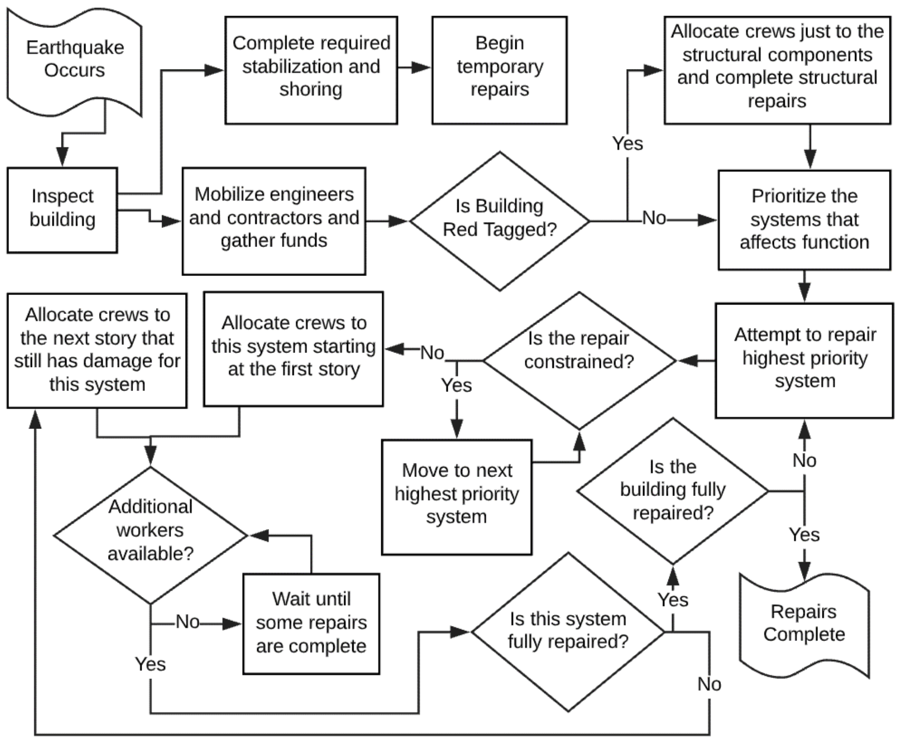

Figure 11. Flowchart illustrating the proposed repair schedule algorithm.

RECOVERY TIME ILLUSTRATION AND UNCERTAINTIES

All of the impeding and temporary repair times are random variables. Contractor mobilization are assumed to be uniformly distributed between the provide minimum and maximum values; all other times follow a truncated lognormal distribution, truncated at +/-2 standard deviations in natural logarithm space, with median values as described in the tables above and a lognormal standard deviation of 0.6. Crew sizes and worker allocation limits are treated deterministically, but repair times for components are randomly generated from the component worker-day repair times in the FEMA P-58 database (FEMA 2012; 2018).

The time to achieve a building performance state, considering impeding times and the repair schedule, is illustrated for a single realization of the Monte Carlo simulation in Figure 12. In this example, initial function is restored to portions of the building after some initial temporary repairs and the repair of the HVAC system; function is restored to the upper stories of the building when the elevator is repaired 175 days after the earthquake.

METHOD LIMITATIONS

While the proposed framework for assessing functional recovery provides a novel approach to relate component-level damage to system-level performance and then to building-level function, it is important to note that many of the assertions as to the severity and extent of damage that would hinder the occupancy or function of a building or tenant are based on engineering judgment, due to the scarcity of empirical data on building functional recovery. Nevertheless, we attempt to build a "ground-up approach," targeting the underlying fundamental causes of loss of function in a building, e.g., loss of a critical building system or ratio of usable interior area. We used engineering judgement to provide default values for each decision variable within the proposed method in such a way that any building that can be analyzed using FEMA P-58 (2012; 2018), can also be assessed for functional recovery using the current assumptions; many of these assertions can easily be modified by a future user of the method in the companion code repository.

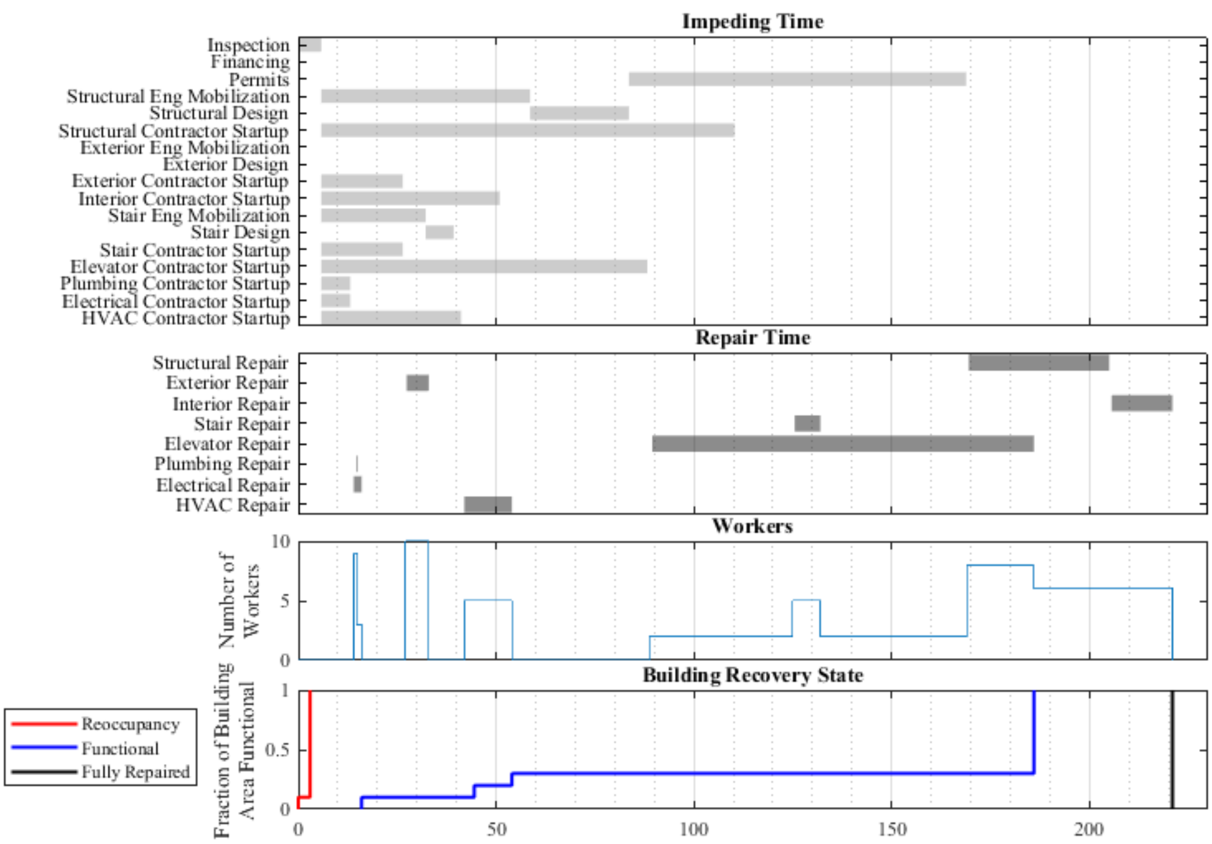

Figure 12. Example output of recovery time module, showing recovery trajectories for a single realization of the functional recovery assessment.

Throughout the method, we define several damage acceptance thresholds to help facilitate mapping of component damage to system- and building-level performance; for example, more than 50% of the building entrance and exit doorway must be accessible to maintain safe egress, and no more than 10% of an interior space may contain falling hazards. These thresholds are simplifying assumptions intended to represent inherent redundancies in various building systems. Each of these assumptions in the proposed method is documented in Table S2 of the electronic supplement; future user of the proposed method may choose to modify or replace these thresholds based on available data.

Several sources of damage and loss of function are not currently considered in this study, such as flooding or external lifelines, and could be added for a more complete assessment. Component damage and consequences not covered in the existing FEMA P-58 Database (2012; 2018) are also not currently considered. Impeding times do not consider long lead time components, nor the time needed to procure and set up temporary elevators and cranes. Additionally, decisions made in the development of the proposed method were calibrated with U.S. construction in mind.

The proposed method is designed to be modular in nature. Future users of the method can the replace repair schedule and impeding factor algorithms with updated methods, remove or replace temporary repair logic, add additional systems and associated fault trees, modify branches of the provided fault trees, and easily update component damage attributes or modify thresholds to suit the needs of their project. Work is ongoing to integrate external factors, such as availability of power, gas, and telecommunication, in this framework. While the fundamental framework proposed is widely applicable, assumptions regarding the repair scheduling algorithm, worker allocations, impeding factors, damage thresholds, and specific component fragility and damage consequences should continue to be revised as better data becomes available, paying special attention to applications beyond U.S. construction.

CONCLUSIONS

The long-term effects that disasters have on communities have motivated engineers and policy makers to seek new methods of improving community resilience through the development of building standards focused on improving a building's capacity to avoid, or quickly recovery from, loss of building function after a hazard event (EERI, 2019; NIST & FEMA, 2021). This paper describes a new performance-based assessment method, based on the architecture of PBEE as implemented in FEMA P-58 (2012; 2018), to explicitly quantify the building performance in terms of reoccupancy, function, and full repair, including the time to regain these performance states, thereby operationalizing this concept.

The proposed method probabilistically quantifies each building performance state, considering the operational performance of individual systems within the building and the occupancy- and tenant-specific requirements of those systems. To map component-level damage to building-level performance states, the method aggregates component damage into building systems, and presents a series of fault trees to define the explicit relationships between component-level damage, system-level operation, and building-level performance, considering safety, access, and function. The unit of analysis is the tenant unit, facilitating the quantification of partial building function when applicable. A building's recovery trajectory over time is assessed with a repair schedule that prioritizes restoration of function, and considers impeding factors and temporary repairs, and is sensitive to the level of building damage.

The method leverages component-level fragility and damage consequences data assembled in FEMA P-58 (2012; 2018) and builds upon that data to provide the component-level and system-level data needed for engineers to perform probabilistic functional recovery assessments. The method is intended to quantify and identify specific damage and response characteristics leading to the loss of building function, with the intent of facilitating the design and retrofit of resilient structures, supporting resilience-based policies and design standards that are of national and local interest.

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