Seismic Performance Assessment of Buildings

Volume 8 – Methodology for Assessment of Functional Recovery Time

Preliminary Report

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Cover photograph – TBD.

Table of Contents

Chapter 1 Introduction

This report describes a preliminary methodology to assess seismic performance in terms of the probable functional recovery time of individual buildings subjected to a damaging earthquake, based on their unique site, structural, nonstructural, and occupancy characteristics. The methodology and procedures are applicable to new or existing buildings, and can be used to: (1) assess the probable performance of a building; (2) design new buildings to be capable of providing desired performance; or (3) design seismic upgrades for existing buildings to improve their performance.

1.1 Background

The functional recovery methodology is based on the general methodology and recommended procedures described in the FEMA P-58, *Seismic Performance Assessment of Buildings, Methodology and Implementation* (FEMA, 2018), and can be applied to seismic performance assessments of any building type, regardless of age, construction, or occupancy. Implementation of the methodology requires basic data on the vulnerability of structural and nonstructural components to damage (fragility), and estimates of potential consequences associated with this damage, including casualties, repair costs, repair times, environmental impacts, placarding (red-tagging), temporary repair measures, occupancy impacts, functional impacts, and impeding factors.

1.2 Scope

The functional recovery methodology explicitly quantifies building performance in terms of three discrete recovery states: reoccupancy, functional recovery, and full functionality. The methodology probabilistically quantifies the level of building recovery at any point in time after an earthquake, based on simulations of building damage and estimates of the impact of that damage on the ability to occupy tenant spaces within the building, and the ability of those spaces to serve their intended pre-earthquake functions.

1.3 Definition of Terms

<<Editorial note: terminology used in this report should be consistent with the FEMA P-2090/NIST SP-1254 report to Congress>>

Recovery time is a metric, measured in days, of how long it takes to achieve a desired recovery state (i.e., reoccupancy, functional recovery, or full functionality) after an earthquake occurs (e.g., Almufti and Willford, 2013; EERI, 2019; FEMA, 2019; NIST/FEMA, 2021). Recovery time includes the time taken to make repairs, as well as any factors or actions referred to as impeding factors, that slow the start of those repairs (Almufti and Willford, 2013). The recovery trajectory is a temporal metric that indicates the level of building recovery throughout the recovery process (e.g., Bruneau et al., 2003; Jacques et al., 2014; Burton et al., 2015; Mieler et al., 2016; Lin & Wang, 2017; Koliou et al., 2018), as illustrated in Figure 1. The recovery states tracked in this methodology are (1) reoccupancy, (2) functional recovery, and (3) full functionality. These three recovery states are commonly used to define the post-event recovery of a building (e.g., Bonowitz, 2011; Burton et al., 2015; NIST/FEMA, 2021).

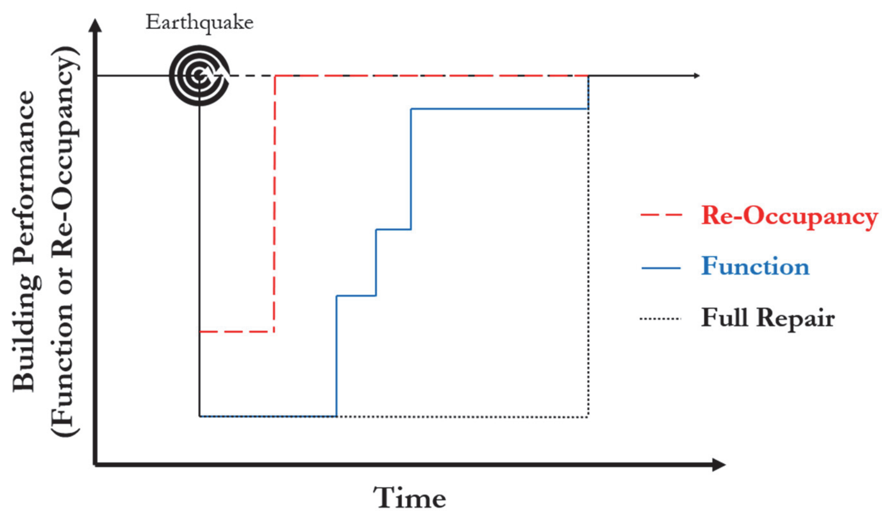

Figure 1 Illustration of building-specific recovery trajectories for reoccupancy, functional recovery, and full functionality recovery states. Steps in the recovery trajectories coincide with repairs to various building systems that lead to changes in the recovery state of one or more tenant units.

Reoccupancy is the building recovery state at which the building (or tenant space) is safe for occupancy, and can be used for shelter (e.g., SPUR, 2012; Almufti and Willford, 2013; FEMA, 2019). Although, in this state, the building may lack critical systems essential to function, the building is habitable and free from disaster-caused hazards to occupant health and safety.

Functional Recovery is the building recovery state at which a building can be used for its “basic intended functions.” As defined in FEMA P-2090/NIST SP-1254, *Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time* (NIST/FEMA, 2021), basic intended functions are less than full pre-earthquake functionality, but more than what would be considered the minimum sufficient for reoccupancy of buildings. For example, an office building or factory is ready to get back to business but might have reduced capacity. Depending on building occupancy type, this capacity can be quantified by a number of metrics, such as patient waiting times in hospitals (Cimellaro & Piqué, 2016), or the floor area of usable space in an office building (Mitrani-Reiser et al., 2012).

Full Functionality is the building recovery state in which all building repairs have been completed, including repair of items that were not required for regaining occupancy or achieving functional recovery, and the building is serving all pre-earthquake functions.

A *tenant-unit* is defined as a space within a building that serves a unique purpose and may have different requirements to function than other spaces within the building due to its intended use or ownership. Buildings can be made up of one or many tenant-units. Examples include individual apartments within a residential building, or a data processing room within an office building.

<<Editorial note: limit citations to the most relevant, and use only in cases where source material is being used in this report>>

1.4 Relation to Previous Methods

The FEMA P-58 methodology probabilistically quantifies the consequences of earthquake damage in terms of repair costs, repair time, casualties, unsafe placards, and environmental impacts. While some researchers, such as Cimellaro and Pique (2016), have used building repair times to implicitly quantify building function by assuming the repair of all damage is needed for function, earlier versions of FEMA P-58 did not explicitly consider the recovery of building function or impeding factors that can delay start of repairs after an earthquake.

The Resilience-based Earthquake Design Initiative for the Next Generation of Buildings (REDi) (Almufti & Willford, 2013), expanded on the FEMA

P-58 methodology to probabilistically quantify building reoccupancy and functional recovery times. REDi also added estimates of time for pre-repair impeding factors, as well as a more sophisticated procedure for scheduling repairs (beyond the serial and parallel assumptions in FEMA P-58).

This method uses the architecture of FEMA P-58 to explicitly quantify loss of building function and time to restore function for a wide range of building types and occupancies and different shaking levels, integrating the functional recovery assessment within the FEMA P-58 probabilistic assessment. The method defines a new reoccupancy 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 reoccupancy and function. This new logic is implemented as a series of fault trees, inspired by work from Porter and Ramer (2012), Jacques et al. (2014), and Mieler et al. (2016). In defining recovery time, it conceptually adopts the REDi (2013) impeding factors and certain aspects of repair scheduling proposed in REDi and Yoo (2016), but with significant differences in details of the structure and the adopted values.

1.5 Limitations

<<Editorial note: discussion of limitations in the methodology to be developed>>

1.6 Organization and Content

This volume describes the functional recovery methodology and the procedures for developing information used as inputs to the methodology.

Chapter 2 presents an overview of the methodology and the framework for assessing occupancy and functional recovery states.

Chapter 3 describes assessment of reoccupancy, including the framework and logic for building safety checks, unsafe placarding, and story access.

Chapter 4 describes assessment of function, including the framework and logic for how damage to key systems impact functionality.

Chapter 5 describes the quantification of recovery time, including impeding factors and scheduling of repairs.

<<Overall editorial note: contrary to typical flow charts, fault trees appear to read from bottom to top. Can (or should) this be adjusted?>>

<<Overall editorial note: description of the methodology would benefit from more narrative discussion of the logic embedded in the fault trees, and clear enumeration of default assumptions for each check.>>

Chapter 2
Methodology Overview

2.1 Framework

The functional recovery methodology supplements the FEMA P-58 methodology by adding an assessment of building recovery times to the quantitative assessment of other earthquake consequences. Hazard assessment, structural analysis, and damage assessment procedures all utilize the procedures outlined in FEMA P-58. Then, for each realization, damage to structural and nonstructural components is used to explicitly quantify the safety and functionality of building systems. Building-level recovery states are quantified based on an aggregation of impacts that each system has on reoccupancy and functionality of tenant units within the building.

The general approach and logic for assessing building function is illustrated in Figure 2. First, for a building to be functional, the building must be safe to enter and re-occupy. Then, each story of the building must be accessible (i.e., each story has appropriate capabilities for egress), and tenants must be safe from local falling and other safety hazards. Finally, tenant units in the building must be able to provide their basic intended functions within the tenant space.

In Stage 1: Building Safety, the building is checked for occupant safety hazards that would cause the whole building to be shut down, 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 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. Building Safety, Story Access and Tenant Safety are required for reoccupancy of a particular space. Function requires reoccupancy and Tenant Function requirements to be met, with the latter being tenant-specific.

<<Editorial note: built into the methodology, we make a number of assumptions (e.g., what triggers a red tag; what systems might be necessary for reoccupancy; what impacts function; and what constitutes "basic function"). We need an upfront section outlining our series of assumptions so users know what is built in and what they might want to change >>

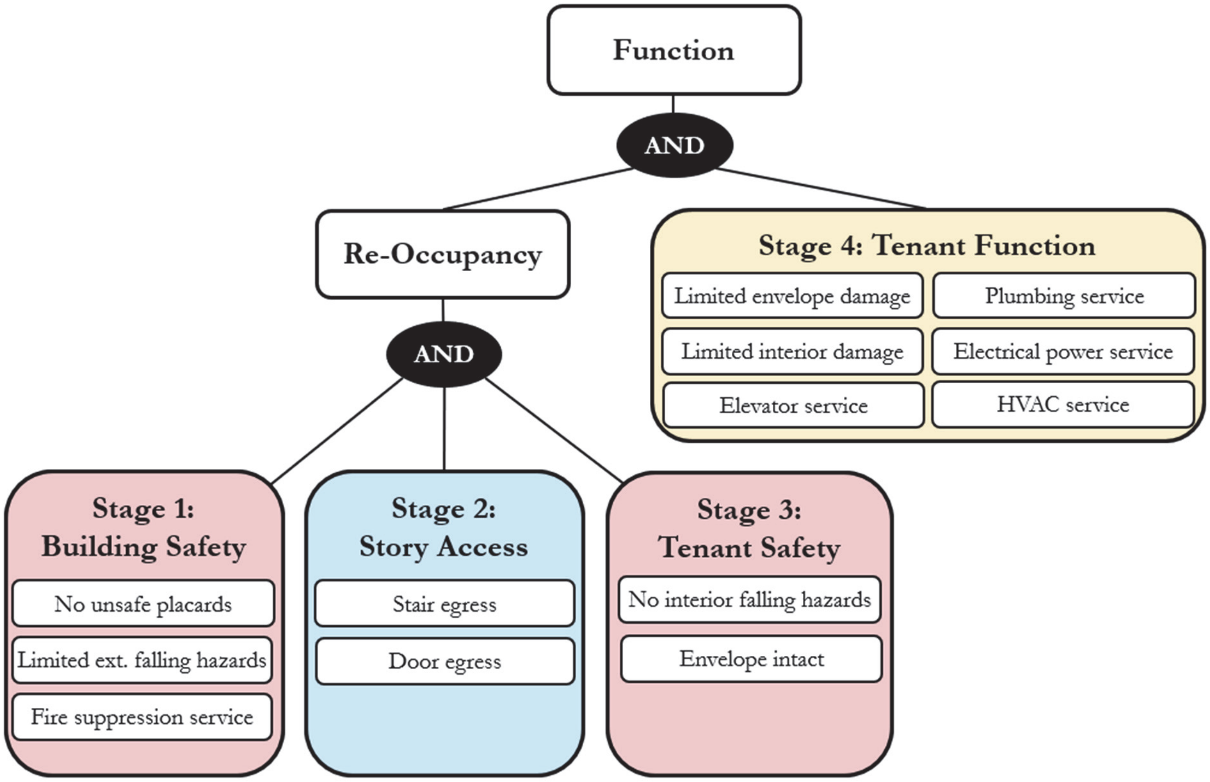

Figure 2 Four stages of function assessment.

The functional recovery methodology recognizes that building function may be specific to the functional requirements of 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 aggregation 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 following, e.g., Porter and Ramer (2012), Jacques et al. (2014), and Mieler et al. (2016). These fault trees are used to define the effect that component damage has on condition or operation of nine different building systems (defined in

Table 1), based on assumptions as to how the condition or operation of each systems affects the reoccupancy or functionality of each tenant unit within the building. 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.

The following sections define the logic and assumptions used in the functional recovery methodology to assess building performance for each stage and building system. These sections also develop and describe a repair scheduling algorithm and method of quantifying impeding factors used to assess how building function is restored over time.

2.2 Required Building and Tenant Information

The FEMA P-58 Building Performance Model is expanded to include tenant-specific information necessary to quantify building function at the tenant-unit level, including occupancy (e.g., residential, office, hospital), location of each tenant-unit within the building, and structural and nonstructural components and systems associated with each tenant unit within the building.

Table 1 Building Systems Defined, and Relevant Assessment Stage

System	Relevant assessment stage	Components in system
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 Components	Tenant Safety Tenant Function	Interior walls, ceilings, lighting, flooring, 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
Telecommunications/Data		
Contents		Tenant-Specific Requirements for Function

<<Editorial note: highlighted cells added during FRRC review>>

2.3 Tenant Requirements

In order to function within a space, each tenant may have unique requirements for building services or tolerance for damage. Typically it is expected that similar types of tenants, with a shared occupancy type, will have similar functional needs. Table 2 provides the set of default assumptions for tenant requirements for office and residential occupancy types.

<<Editorial note: what about assumptions for other occupancy types?>>

These default requirements are based on assumptions and engineering judgment, with the intent to outline the types of damage that would hinder function in commercial office and residential spaces, but with easily modifiable thresholds if other requirements are considered. For example, HVAC systems may not be needed in all climates especially if units have operable windows or other passive ventilation systems.

Table 2 Example Default Requirements for Building Systems for Tenant Function

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Performance Metric</th><th colspan="2">Default Tenant Requirements for Function</th></tr>
<tr><th>Office</th><th>Residential</th></tr>
<tr><td>Exterior Enclosure</td><td>Percent of the perimeter area boarded up or with severe damage</td><td>< 50% perimeter affected</td><td>< 75% perimeter affected</td></tr>
<tr><td>Structural and Interior Components</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 elevator operational per 1000 occupants[1]</td><td>Units above the 5th story need at least one elevator operational per 1000 occupants[1]</td></tr>
<tr><td>Plumbing</td><td rowspan="3">Level of service provided</td><td rowspan="3" colspan="2">System operational in unit</td></tr>
<tr><td>Electrical</td></tr>
<tr><td>HVAC</td></tr>
</table>

[1] Elevator needs are taken as one-quarter the typical design requirements for new design (which requires 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.

Chapter 3
Assessment of Building Reoccupancy

3.1 Building Safety

3.1.1 Framework of Building Safety Checks

In Stage 1 (Figure 1), safety is checked at the building level. This check identifies whether damage exists that can lead an entire building to be unsafe to occupy (e.g., structural safety concerns, presence of external falling hazards, and risk of fire following earthquake). The effect that each of these conditions has on the assessment of Building Safety is quantified using the fault tree shown in Figure 3.

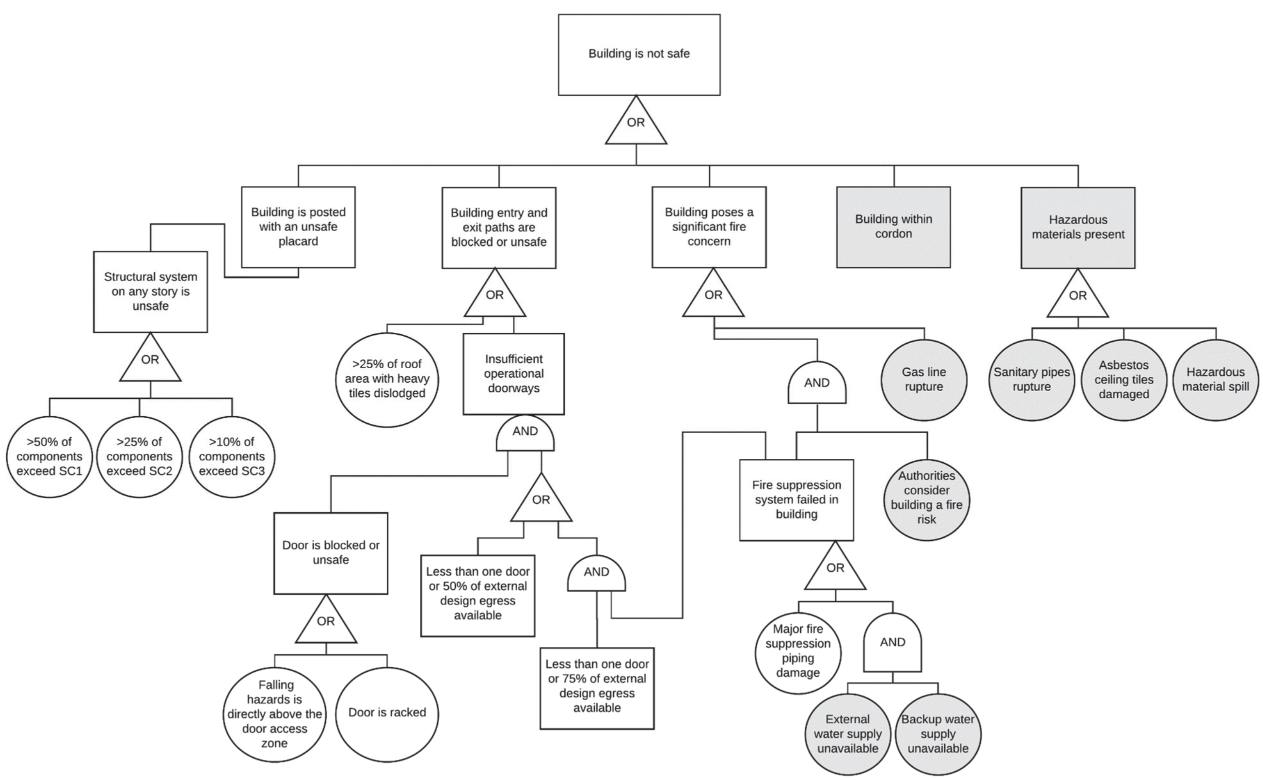

Figure 3 Fault tree determining Building Safety (Stage 1). Gray events are not currently considered. Safety Classes (SC) used in defining the unsafe placarding decisions.

If any of these conditions are determined to exist based on the damage to each system, the building is flagged as unsafe, and all tenant-units within the building are deemed neither occupiable nor functional.

3.1.2 Updated Virtual Inspector for Identifying Unsafe Placards (Red Tags)

Studies by Cook, et. al. (2021) suggest that the existing procedure for determining unsafe placards in FEMA P-58 over-predicts the experience recorded in the Northridge earthquake by several orders of magnitude. Therefore, the procedure for determining unsafe placards has been updated, as described herein.

<<Editorial note: we need to be more explicit and complete in describing changes to the FEMA P-58 process for identifying unsafe placards>>

In the updated procedure, the process has been modified to aggregate component damage through a system-based virtual inspection process, as shown in Figure 4. In this system-based approach, each component is assigned to a structural system, and rather than checking for unsafe placards in each component performance group, the virtual inspector checks each structural system for excessive amounts of damage that would indicate a significant deterioration in performance.

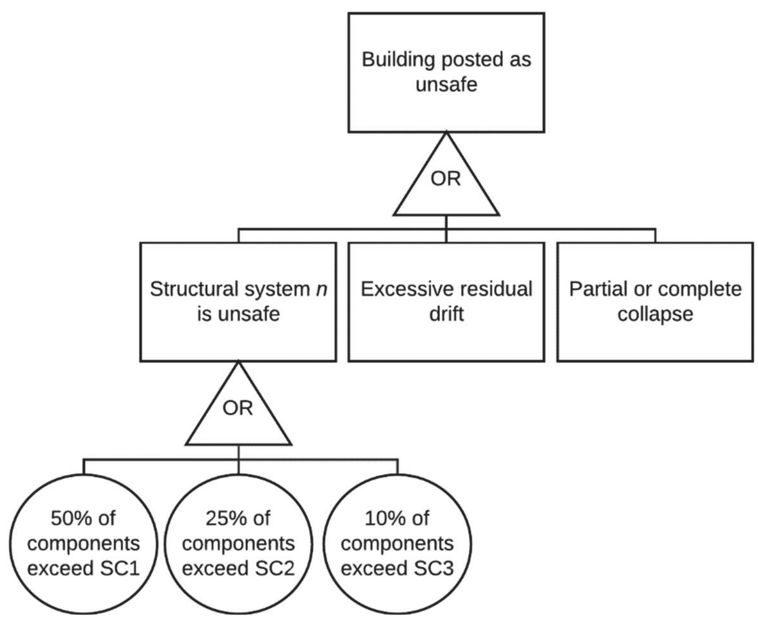

Figure 4 Proposed virtual inspection process at each story, where structural system *n* represents each structural system in the building, and SC denotes the safety class defined in Table 4.

The structural systems, which include lateral and gravity systems and some roof systems, are shown in Table 3, with the intent of grouping component damage systems that lead to similar global failure mechanisms.

Table 3 Structural System Groupings for Virtual Inspection Process

Structural System ID	Type of System	Components in Structural System Group Check	Additional Components to Check
1	RC shear wall lateral or bearing wall system	Squat RC shear walls Slender RC shear walls	RC link beams
2	Reinforced masonry bearing wall system	Flexure-controlled reinforced masonry walls Shear-controlled reinforced masonry walls	
3	Precast tilt-up bearing wall system	Precast tilt-up panels	
4	Light framed bearing wall system	Wood light frame walls Steel light frame walls	
5	Steel braced-frame lateral system	Steel concentric braces Steel eccentric braced frame links Steel buckling restrained braces	Column splices Steel base plates
6	Steel moment-resisting frame lateral system	Steel moment frame connections	Column splices Steel base plates
7	RC moment-resisting frame lateral system	RC moment frame connections	
8	RC slab-column gravity system	RC slab-column connections	
9	Steel column gravity system	Bolted shear tab beam connections	
10	Flexible wood diaphragm roof system	Flexible wood diaphragms	Wall-to-diaphragm connections

<<Editorial note: we need to explain how buildings with combinations of structural systems are addressed>>

The virtual inspector checks each structural system separately on each story. For example, in a multi-story building that is rectangular in plan, the virtual inspector would check the lateral system in one direction, then the lateral system in the orthogonal direction, then the gravity system (if separate), on each story (three checks total per story in this example). A separate check would be made of the roof system (if flexible).

In addition to defining the grouping of components, Table 3 lists additional checks needed to capture the various failure mechanisms for selected structural system groups. For example, steel column splices and steel base plates are separate fragilities in the FEMA P-58 database, but are both located at a single column; failure of the column occurs if either the column splice or the base plate fails.

Ideally, these fragilities could be aggregated into a single fragility or subassembly when counting failed components in the unsafe placard check. However, to combined fragilities into subassemblies, new subassembly fragilities would be needed, either based on new test data or aggregated based on engineering judgement. Instead, the number of damaged components for any additional component fragilities are checked against an acceptance threshold separately from the structural system check.

To quantify the deterioration of each structural system, the damage states for each component within the FEMA P-58 fragility database are assigned to a Safety Class (SC), which indicates the severity of damage and the level of concern an inspector would have when observing the damage. Each SC, defined in Table 4, has an associated acceptance threshold, which indicates the percentage of damaged components in a particular system, story, and direction that, if exceeded, will result in a virtual inspector posting an unsafe placard. The SC assignments and acceptance thresholds are based on the judgment of the project team, informed by ATC-20 guidelines (1989; 2005).

Table 4 Safety Class Definitions and Thresholds

Safety Class	Description	Acceptance Threshold
0	Slight damage that is not a safety concern and will never trigger an unsafe placard.	--
1	Moderate damage that may be visually concerning, but does not substantially reduce the lateral strength of the building.	50%
2	Severe damage that causes substantial loss of lateral strength of the component, but does not substantially reduce its vertical load carrying capacity.	25%
3	Severe damage that compromises vertical load carrying capacity of the component	10%
4	Failure of a column that jeopardizes stories above or below, or the whole building	1 (each)

<<Editorial note: highlighted cells added during FRRC review>>

Based on this information, the virtual inspector goes through each structural system in the building and quantifies the fraction of damaged components in each structural system in a story and direction that are associated with each SC. For any SC, if the fraction of damage components in SC_i or greater exceeds the acceptable threshold, on any story, the building is posted as unsafe. To define uncertainties in the proposed acceptance thresholds, we adopt the default FEMA P-58 lognormal standard deviation of 0.5 when sampling thresholds for each realization of the Monte Carlo simulation in the FEMA P-58 framework. A complete table of the SC and structural system component assignments is provided in the supplementary table titled FragilityDatabase_UnsafePlacards.csv.

<<Editorial note: we will need to decide how to present the various functional recovery spreadsheets (e.g., narrative description in report; more detailed information in an appendix, and then full information in its entirety as part of the supporting electronic materials in FEMA P-58, Volume 3)>>

3.1.2.1 Updates to Unsafe Placarding of Wood Light-Frame Buildings

Adjustments have been made in the evaluation of wood light-frame buildings based on empirical evidence and expert feedback to reduce the number of predicted unsafe placards to better match historical data from past earthquakes. The updated virtual inspection process reduces the influence of damage to nonstructural components and individual wood walls.

<<Editorial note: we need to cite this evidence and feedback or describe in more detail>>

In large wood frame buildings (i.e., wood frame buildings greater than two stories), the virtual inspector only checks local wood wall damage, such as fractured studs. The contribution of nonstructural damage to unsafe placarding has been removed. This is consistent with the original virtual inspection process proposed in Mitrani-Reiser (2007), which also solely relied on structural damage to indicate unsafe placards.

In small wood frame structures localized wall damage does not warrant an unsafe placard, especially in single-family wood frame buildings. Unsafe placards are triggered only by global failure mechanisms, such as collapse or excessive residual drift. Permanent lateral deformations are considered excessive when large enough to cause significant lateral or vertical instabilities due to P-Delta effects, typically around 1-2% for most buildings. Recent studies, however, have shown that wood light-frame systems can experience higher residual drifts without collapse, e.g., FEMA P-2139 series of reports (FEMA, 2020).

3.1.3 Safe Entry and Exit

Falling hazards on the outside of the building may pose a risk to occupants entering the building. External falling hazards may come from broken and dislodged cladding, broken glass, severely damaged chimneys, roof tiles, and masonry parapets (ATC, 1989; 2005). In this method, to identify the types of damage that trigger external falling hazards, each component damage state within the FEMA P-58 fragility database is assigned a falling hazards flag

(1 = Yes; 0 = No). Falling hazard flags (Yes) are assigned to damage states corresponding to major damage in exterior components, such as glass breakage, failure of cladding anchorage, or severe racking of external walls. A detailed list of all component damage states associated with external falling hazards is provided in the supplementary table titled FragilityDatabase_Function.csv.

Falling hazards are treated as a safety concern if a sufficient number of building entrances or exits are blocked or unsafe, as indicated in the fault tree shown in Figure 5. 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. If the specific location of each falling hazard or building exit is not tracked in the performance model, the aggregate length of falling hazards on each side of the building can be estimated by first determining the linear feet (in plan) affected by falling hazards at each story, then combining these lengths using a square root of the sum of the squares approach; this simplified approach reflects the fact that falling hazards may be co-located along the length of the building in multiple stories. The probability of the building exit being marked as unsafe due to a falling hazard can then be calculated based on the aggregated length of falling hazards on a given side and the width of the door access zone.

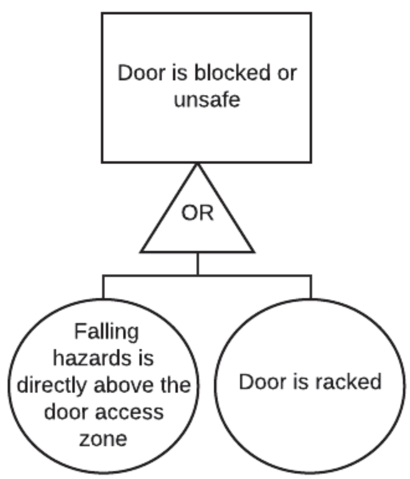

Figure 5 Fault tree showing how falling hazards affect Building Safety at exit and entry paths.

Some falling hazards can be mitigated prior to their full repair (e.g., by boarding up broken windows and glazing). In this study, all exterior components in the FEMA P-58 fragility database are assumed to be temporality repairable, but the effort needed to make the temporary repair, and subsequent length of time required, varies based on the type of component and level of damage. For instance, boarding up a broken window is quicker and requires less expertise compared with securing a damaged precast cladding panel. Once a falling hazard is temporarily repaired, it no longer affects Building Safety. A list of the components that can be temporarily repaired and the time required to temporarily repair each component is provided in the supplementary table titled FragilityDatabase_Function.csv.

If a sufficient number of entrance doors in the first story are damaged or considered unsafe for access, the whole building is deemed unsafe, as indicated in the fault tree logic shown in Figure 6. The safety check assumes that there is at least one functioning entrance and exit, or 50% of the required design egress for the building (International Code Council, 2009), for a building to be deemed safe to access in a post-earthquake setting.

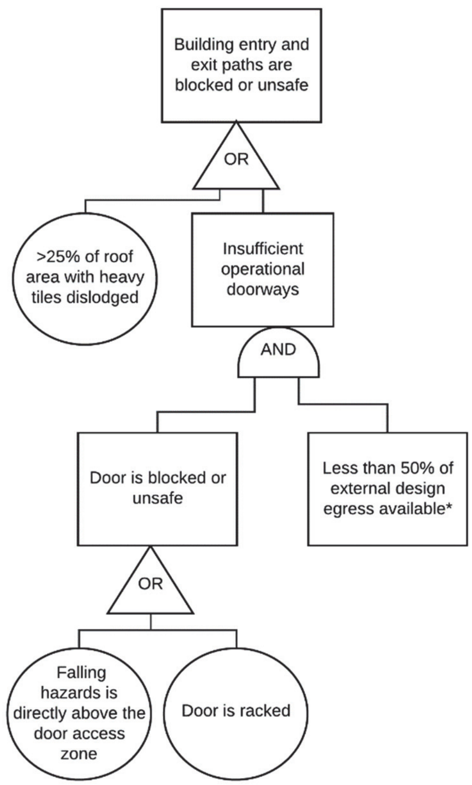

Figure 6 Fault tree showing relation between inoperable doorways, falling hazards, and Building Safety.

Justification for acceptance of fewer egress routes than would otherwise be required by the code is justified by the expectation that requirements would likely be relaxed for a period of time following an earthquake to encourage building occupancy (FEMA, 2019). However, if the fire suppression system is not functioning at a given story, it is assumed that egress requirements would be more stringent. When the fire suppression system is not operating properly, egress requirements are increased to at least 75% of design egress.

3.1.4 *Fire Safety and Fire Suppression*

Fire suppression systems are used to help mitigate fire risk. FEMA P-2055 (FEMA, 2019) provides guidance 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 placed on the building and the fire suppression system is restored within 30 days after the earthquake. Therefore, in the functional recovery methodology, failure of the fire suppression system (assessed through the fault tree in Figure 3) only results in the closure of the building if the building officials or fire marshals having jurisdiction consider the building to be a fire risk. A list of the component damage states associated with the fire suppression system is provided in the supplementary table titled FragilityDatabase_Function.csv.

3.1.5 *Other Building Safety Issues*

Other types of damage may also cause a building to become unsafe or inaccessible for occupancy. These include the presence of hazardous materials, such as asbestos wall boards and ceiling tiles, which created several reoccupancy issues after the 1994 Northridge Earthquake (ATC, 2000), and the use of building cordons, which caused extensive building closures after the 2011 Christchurch Earthquake (Mieler et al., 2016). Hazardous materials and building cordons are not considered, as they are outside the scope of a building-level assessment and FEMA P-58 fragility database.

3.2 Story Access

In Stage 2 (Figure 2), each story is checked for accessibility and egress as shown in the fault tree in Figure 7. 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, egress is hindered, and the story is considered inaccessible. Each story is checked separately, such that if there was enough damage to stairwell doors on the fourth story of a building, all tenant-units in the fourth story would be deemed inaccessible. Likewise, if there is enough damage to the stairs on a particular story, that story and all stories above would be deemed inaccessible, while the stories below would remain accessible.

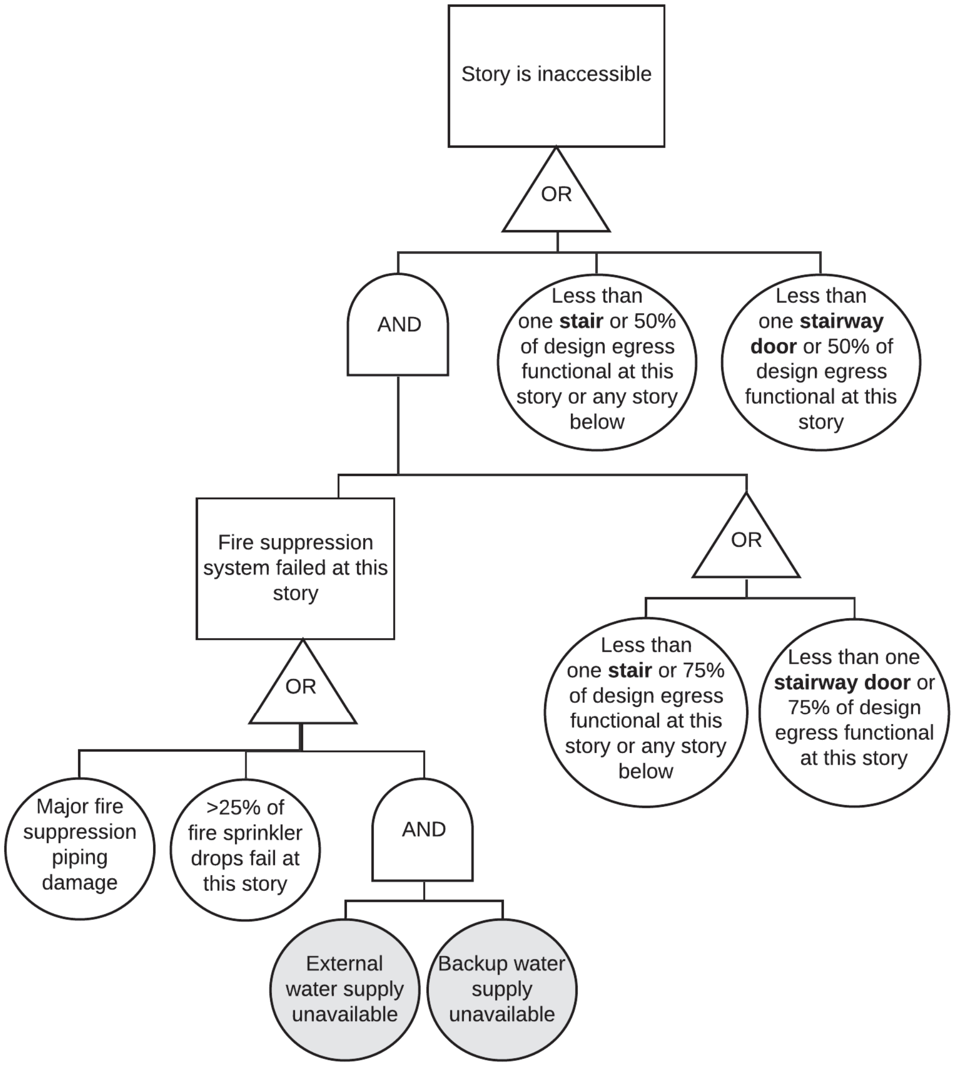

Figure 7 Fault tree determining Story Access (Stage 2). Gray events are not currently considered.

In the Story Access check, only severe damage that impedes the use of stairs and doors affects access and egress. In the stair fragilities in the FEMA P-58 fragility database, damage is classified into three damages states involving: (1) aesthetic damage such as minor local yielding of steel stairs or cracking in concrete stairs; (2) minor structural damage that does not affect live-load carrying capacity; and (3) severe structural damage that does affect the live-load carrying capacity of the stairs. In the Story Access check, only the damage state that impacts the live-load carrying capacity of the stairs (damage state three) is flagged as affecting access; all other damage states are assumed to be aesthetic.

Similarly, door fragilities typically have two damages states. In this case, the first damage state is associated with racking of the door from residual drift.

Therefore, the Story Access check classifies both damage states as resulting in an effect on access. A list of all component damage states associated with stair and door access is provided in the supplementary table titled FragilityDatabase_Function.csv.

The Story Access check assumes that stair and door damage only affects access if sufficient egress is not maintained. Similar to the criteria for safe entry and exit in the Safety check, the criteria for egress in the Story Access check assumes that there is at least one functioning stairway (i.e., both the staircase and stairway door are not too damaged), or 50% of the required design egress. When the fire suppression system is not operating properly, the criteria are increased to at least 75% of design egress.

The effect of door racking on story access can be mitigated prior to a full repair of the door, by unjamming the racked door as a temporary repair. Once a door is temporarily repaired, it no longer affects story access. The Story Access check considers no temporary repair for severe stair damage.

3.3 Tenant Unit (Local) Safety

If the building is both safe and the story is accessible (Figure 2), each tenant unit is checked for local safety hazards using the fault tree presented in Figure 8. These local safety hazards pose a risk to the occupants in specific areas of the building, but are not extensive enough to be caught in the Building Safety check. Local safety hazards include severe exterior enclosure damage, interior falling hazards from structural components, nonstructural components, and tenant contents, and the local presence of hazardous materials. Tenant contents and hazardous materials are not presently considered.

The exterior enclosure of a building helps keep occupants safely inside the building and protected from exterior hazards and debris. Damage that severely comprises the structural integrity of the exterior envelope in the tenant unit, resulting in large openings in the side of the building, causes the tenant unit to be deemed unsafe to occupy (FEMA, 2019). This damage is associated with specific damage states of exterior components in the FEMA P-58 fragility database that are severe enough to compromise the integrity of the exterior envelope, such as precast cladding anchorage failure, broken and fallen glass in curtains walls, and fracture of the studs in light frame walls.

The effects 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). Once exterior components are boarded up and temporarily repaired, they no longer affect tenant safety. A list of all component damage states associated with exterior enclosure damage and temporary repair times is provided in the supplementary table titled FragilityDatabase_Function.csv.

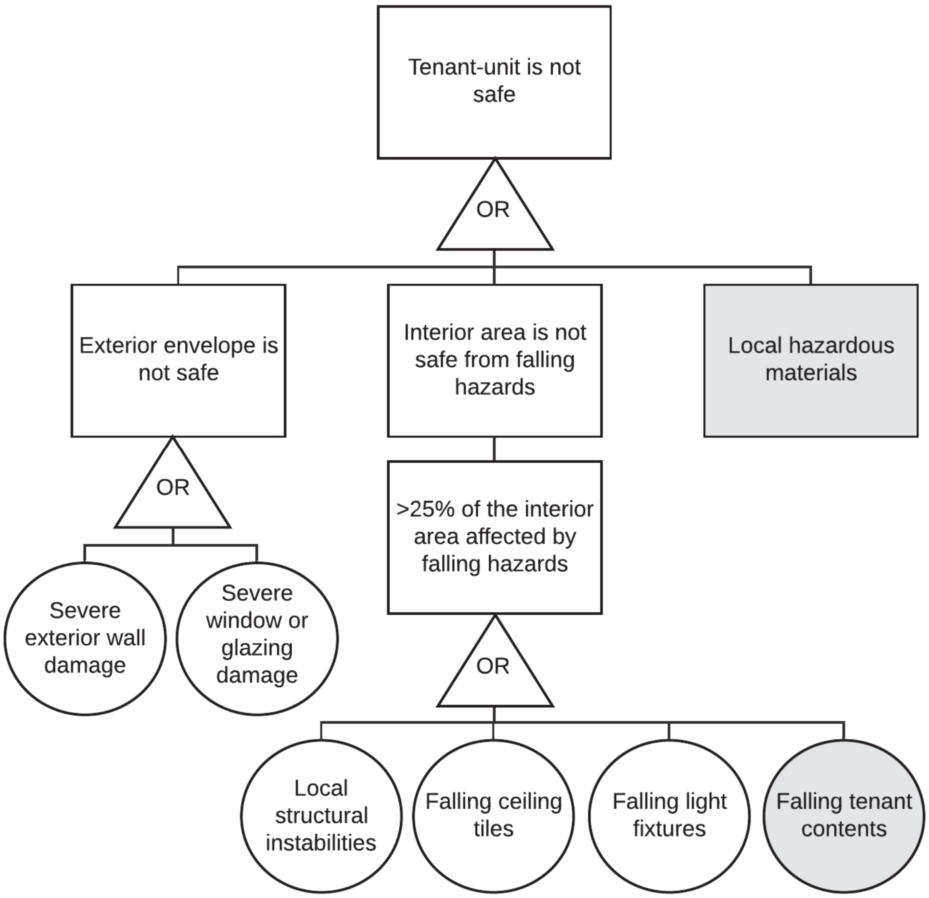

Figure 8 Fault tree determining Tenant (Local) Safety. Gray events are not currently considered.

Interior falling hazards caused by damage to variety of interior components can mean the tenant unit is not safe to occupy (Jacques et al., 2014). The Tenant Safety check assumes that if more than 25% of the interior area of the tenant unit is affected by interior local falling hazards, the tenant unit becomes unsafe to occupy. This threshold is based on judgment. If less than 25% of the interior area of the tenant unit is affected by interior falling hazards, then it is assumed that local falling hazards can be sectioned off and basic function in the space can be resumed (pending other requirements).

Components and damage states that trigger local falling hazard concerns have been identified. A list of all component damage states associated with falling hazards and their affected area is provided in the supplementary table titled FragilityDatabase_Function.csv. For example, minor damage to suspended ceilings does not trigger a falling hazard, but moderate to major damage does. Each component that poses a falling hazard is also assigned a specific area (in plan) that is affected by that falling hazard; the assigned affected areas are typically adopted from the falling hazard casualty logic of FEMA P-58.

<<Editorial note: we need to identify differences and decide whether the affected areas in FEMA P-58 fragilities should be adjusted or not >>

The area affected by each component is combined and used to quantify the total area in the tenant unit that is affected by falling hazards. Affected areas are combined based on the location of each component within the tenant unit (in plan). However, different component, such as suspended ceilings and slab-column connections, 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.

Many interior falling hazards can be mitigated prior to full repair by removing and bracing components as a temporary repair. Once interior falling hazards are secured through a temporary repair, they no longer affect tenant safety. A list of the temporary repair measures is provided in the supplementary table titled FragilityDatabase_Function.csv.

3.4 Logic Governing Reoccupancy Assessment

<<Editorial note: This is a placeholder for the underlying logic in assigning the fragility damage state tags and consequences for reoccupancy. This section may contain a short summary and a table, which describes the underlying logic in the component damage state assignments.>>

Chapter 4
Assessment of Building Function

4.1 Building Function

4.1.1 Framework of Building Function Checks

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 basic function in the tenant-unit. This stage involves quantifying the extent of damage to, and level of service provided by, each system in

Table 1 (e.g., disruption to interior spaces, elevator service, heating ventilation and air conditioning (HVAC) service), and then comparing the performance of each system against a set of tenant-specific requirements to determine if function is affected. If the performance of each system satisfies the tenant requirements in Table 2, the tenant unit is functional.

<<Editorial note: The information in Tables 1 and 2 represent a default set of assumptions. We need to clearly identify what a user can modify in this regard.>>

4.2 Building Envelope

If there are large openings in the building's envelope or many broken or boarded up windows, the building occupants will be less protected from the elements and have less natural light, and may be uncomfortable functioning within the building. Further, in some occupancies, such as food and pharmaceutical production, the FDA and other regulatory agencies require extensive control of environmental conditions that is not consistent with a damaged building envelope. Not all tenant-units and occupancies will be affected the same by exterior enclosure damage.

The exterior enclosure system is checked using the fault tree shown in Figure 9. Cladding damage deemed to affect building function is associated with severe damage that compromises the building envelope and exposes the interior area to the exterior environment. Minor damage such as cracked windows or walls are assumed to have no effect on function. Each cladding component damage state is assigned a flag that indicates the potential for that damage to affect function and the perimeter area that the damage affects (based on the unit of the component) (reported in the supplementary table titled FragilityDatabase_Function.csv). If the extent of exterior enclosure damage, quantified as the percent of the tenant unit perimeter area with cladding damage that affects function, does not satisfy the tenant functional requirements, the tenant unit is considered no longer functional. The default tenant requirements in Table 2 assume that function is possible with a higher permissible extent of exterior wall damage (i.e., 50% of the perimeter area) compared with the Tenant Safety check in Stage 3. However, temporary repairs to the exterior enclosure system (securing walls and boarding up windows) mitigate the effect exterior wall damage on Tenant Safety, but do not mitigate the effect on Tenant Function.

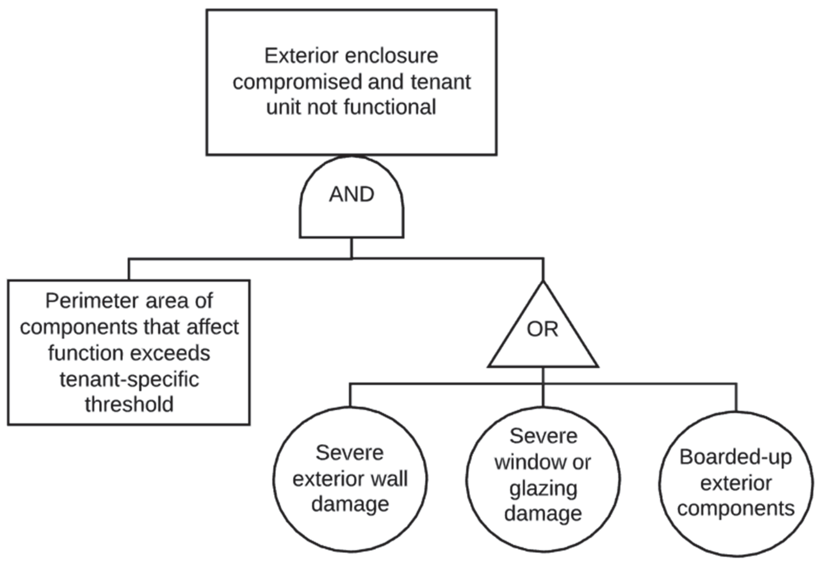

Figure 9 Fault tree defining the performance of the exterior enclosure for the Tenant Function stage (Stage 4).

4.3 Interiors (Structural and Nonstructural)

The presence of interior falling hazards or other safety issues, severely damaged floors, ceilings, or walls, or spilled and scatter 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). Some isolated severe interior damage will likely not impact tenant function, as the tenants will be able to work around affected areas, however, extensive damage throughout a space may cause the entire tenant unit to not be functional, depending on the tenant's tolerance for interior damage.

The building interior is checked using the fault tree shown in Figure 10. Each interior nonstructural and structural component is assigned a flag that indicates the potential for damage to affect function as well as the floor area affected (see the supplementary table titled FragilityDatabase_Function.csv). 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, such as buckled studs and separation of sheathing for interior partition walls. Wall damage only affects interior function for very severe damage states where studs have buckled, and sheathing has separated.

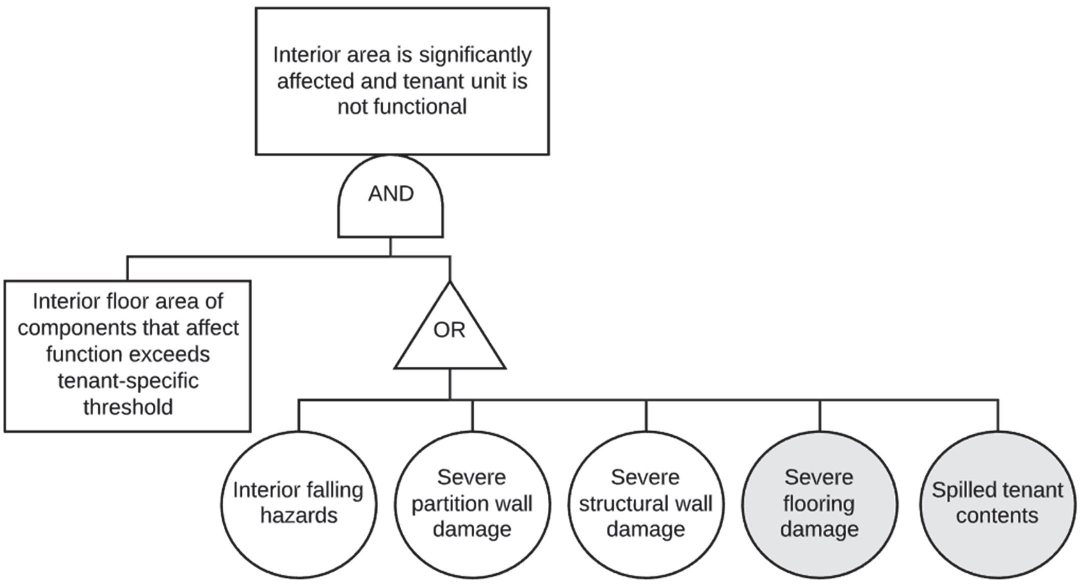

Figure 10 Fault tree defining the performance of the interior system for the Tenant Function stage (Stage 4). Gray events are not currently considered.

In the fault tree for the tenant function check, the interior falling hazards event is the same as the interior falling hazard event in the tenant safety check (Figure 8). However, when assessing function, interior falling hazards are combined with the other events in the fault tree, such as wall damage, that do not affect safety.

The extent of damage to the building interior is quantified by combining the area of all affected interior components within the tenant unit, based on their location within the tenant unit. If specific component locations are unknown, simplified SRSS combination methods, as discussed for Stage 3, can be used to estimate total affected area. If the extent of interior damage is beyond the tenant functional requirements, the tenant unit is considered no longer functional.

Each component is also assigned a temporary repair time to clean up or shore interior damage prior to the full repair in the supplementary table titled

FragilityDatabase_Function.csv. Once component damage is temporarily repaired it no longer affects interior function.

Spilled tenant contents and flooding are likely to affect interior function but are not currently considered in the functional recovery methodology.

4.4 Elevators

While not all buildings and tenant units will need elevators to function, some people and activities (e.g., occupants in high-rise buildings, patient transport services in hospitals), are impacted by elevator operations. The performance of the elevators is checked with the fault tree in Figure 11.

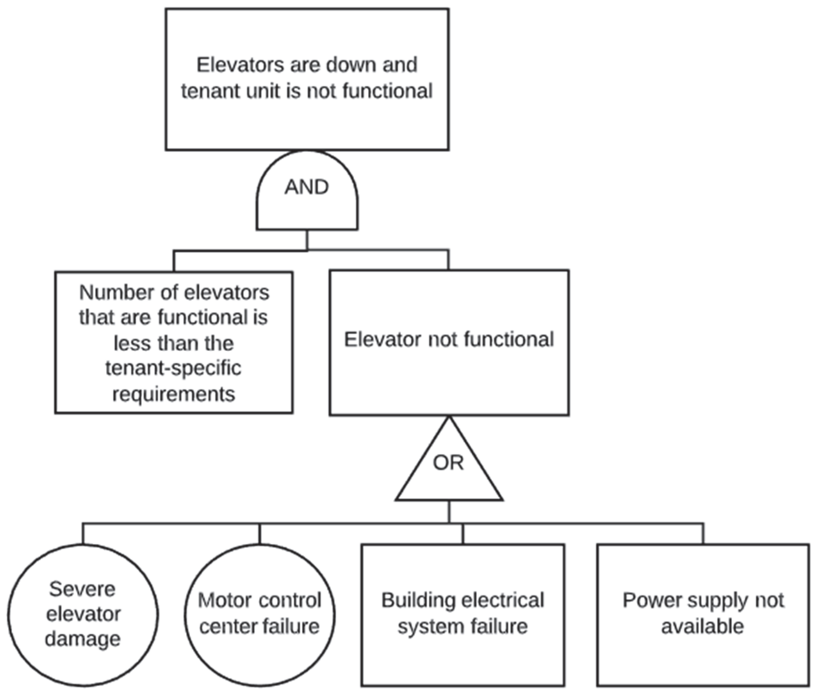

Figure 11 Fault tree defining the performance of the elevators for the Tenant Function stage (Stage 4).

Elevator operation is based on damage to the elevators, 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 will cause the elevators to be inoperable, with the exception of cab ceiling damage and motor control center anchorage damage. Elevators are modeled as independent components, where damage to one elevator may cause the loss of operation of a single elevator; failure of the motor control center or loss of the power supply will cause all elevators in a building to be inoperable. Assessment of the performance of the electrical power system is discussed below.

Because most large buildings have multiple elevators to reduce occupant waiting times, not every elevator is required for function in a post-earthquake setting, as longer waiting times may be deemed acceptable, as suggested in Table 2. A list of all component damage states associated with elevator performance is provided in the supplementary table titled FragilityDatabase_Function.csv.

4.5 Potable and Sanitary Waste Plumbing Systems

Water and wastewater systems in buildings are essential to occupant health and tenant function. Although temporary services could provide short term solutions for shelter, many occupancies, such as hospitals, residences, and offices, need a steady water supply to function at pre-earthquake levels (FEMA, 2019). The performance of the plumbing systems is checked based on the fault tree provided in Figure 12.

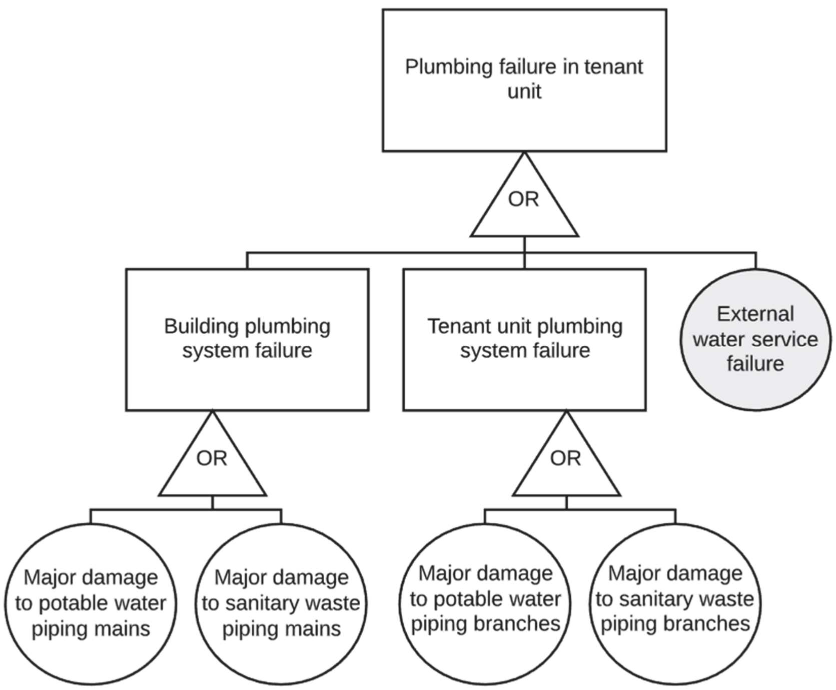

Figure 12 Fault tree defining the performance of the plumbing system for the Tenant Function (Stage 4). Gray events are not currently considered.

Plumbing system operation depends on damage to the potable water piping components, sanitary waste piping components, and the external water supply. The piping components include both large diameter (distribution mains) piping and small diameter (branch) piping. The Building Function check assumes that major damage to a main supply pipe will disrupt the plumbing services to the entire building, while major damage to a smaller branch pipe with only disrupt service to the tenant unit where the pipe is located (note that potential flooding impacts are ignored). Only major pipe damage or rupture (i.e., not minor leakage) affects operation of the plumbing system (see the supplementary table titled FragilityDatabase_Function.csv). The performance of the plumbing system is treated as binary; either the plumbing system is operational in the tenant unit, or it is not.

<<Editorial note: we need to be consistent with FEMA P-58 in how we say external supply systems are considered (or not)>>

4.6 Electrical Power System

Most functions in modern society depend on electrical power to operate, so failure of the electrical power system in a building will likely severely limit the ability of most occupancies to function. Operation of the electrical system at the building level and tenant level is checked using the fault tree in Figure 13.

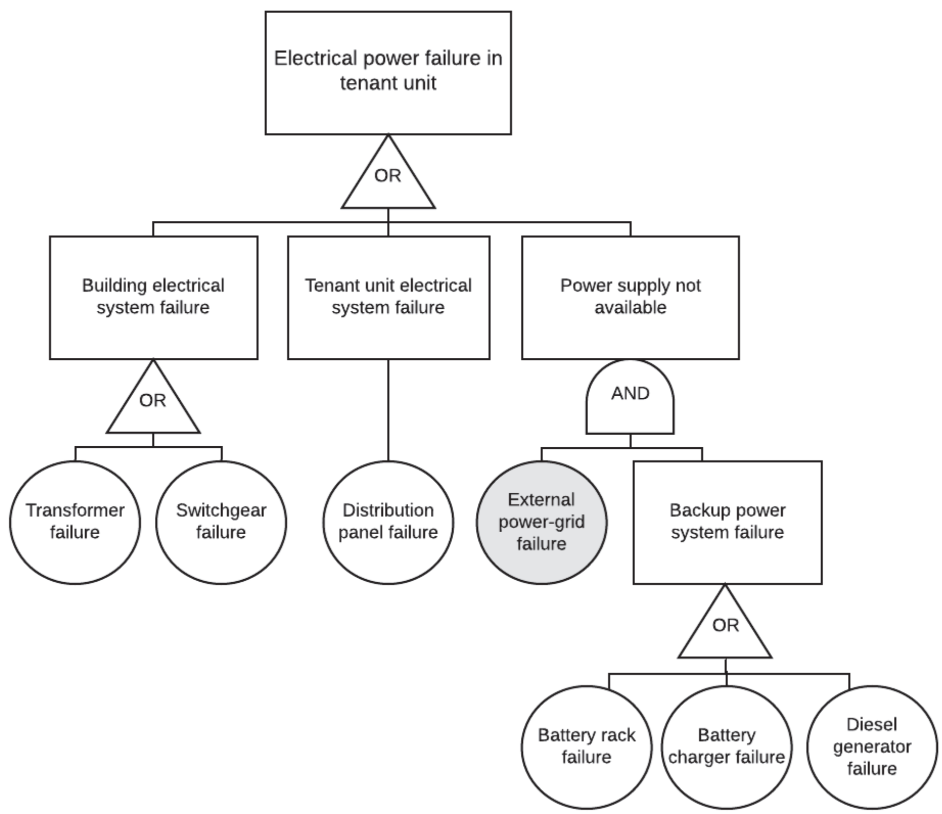

Figure 13 Fault tree defining the performance of the electrical system for the Tenant Function Stage (Stage 4). Gray events are not currently considered.

Electrical system operation depends on damage to the electrical equipment in the building, including the transformers, switchgears, and distribution panels, as well as the external power supply. A detailed list of all component damage states associated with electrical system performance is provided in the supplementary table titled FragilityDatabase_Function.csv.

<<Editorial note: we need to be consistent with FEMA P-58 in how we say external supply systems are considered (or not)>>

Major damage to the transformer or switchgear will disrupt the electrical service for the entire building, while major damage to a distribution panel will only disrupt service to the tenant unit in which the panel is located. Some buildings, such as hospitals, have backup electrical power systems. When such systems are present, they are assumed to mitigate the loss of an external power supply. Major damage to the backup system equipment, however, is assumed to result in loss of the backup power supply for the entire building. Performance of the electrical power system is treated as binary; either the electrical system is operational in the tenant unit, or it is not.

4.7 Heating, Ventilation, and Air Conditioning Systems

The operation of the HVAC system is dependent on heating system equipment, the cooling system equipment, exhaust and fan equipment, air distribution, chilled and heated water distribution, the electrical power supply, and potential natural gas supply. Each HVAC component damage state that affects the operation of the HVAC systems in the supplementary table titled FragilityDatabase_Function.csv.

The configuration of HVAC systems depends on the age, size, and type of building. For example, in large structures, chillers and cooling towers provide chilled water (for air cooling) for the entire building, while air handling units often serve a specific area within the building. Because of differences in HVAC system configuration, three typical HVAC system layouts have been defined: (1) for mid- and high-rise structures; (2) for large low-rise structures; and (3) for small low-rise structures. The overall performance of the HVAC system in the tenant unit is aggregated from the component-level damage using a fault tree associated with each HVAC layout.

The operation of HVAC systems in mid- and high-rise structures is checked using the fault tree shown in Figure 14, which would be different for the other HVAC layouts. Some HVAC equipment components are designed to operate in parallel, such as chillers and cooling towers, such that some component failures can occur without causing system failure. For HVAC equipment that is designed with redundancy, it is assumed that over 50% of the components need to fail before operation of the system is affected. For HVAC distribution components in the tenant unit, such as ducts, drops, in-line fans, and variable air volume boxes, acceptable damage thresholds are provided for each HVAC distribution component, based on judgment, as shown in the fault tree in Figure 14. The performance of the HVAC system is treated as binary; it is functional in the tenant unit, or it is not.

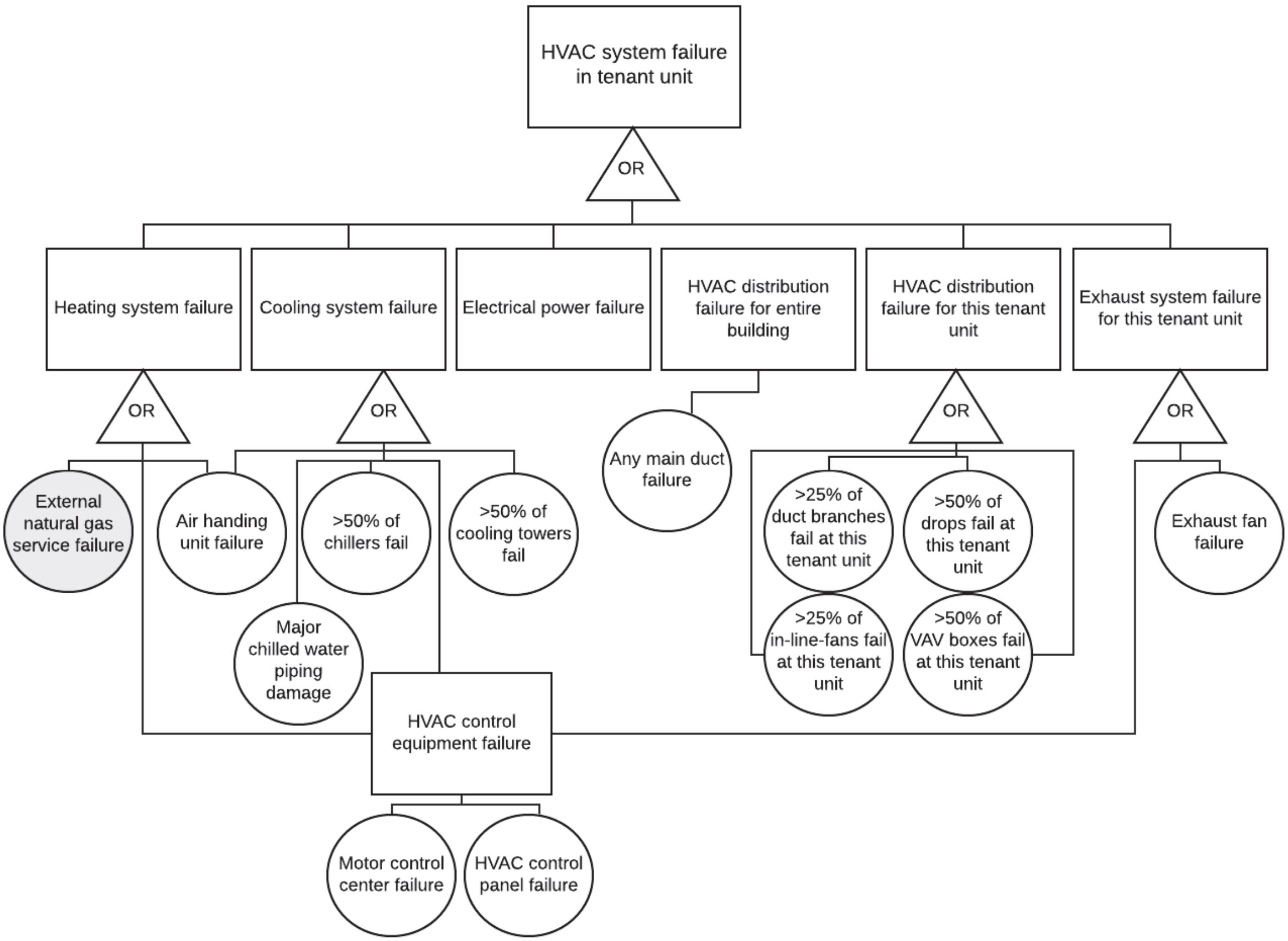

Figure 14 Fault tree defining the performance of the HVAC system in mid and high-rise buildings for the Tenant Function Stage (Stage 4). Gray events are not currently considered.

4.8 Tenant-Specific Contents

<<Editorial note: Many occupancies require tenant-owned equipment to function. For example, most offices can't function unless the server room is functional. A hospital can't function unless the monitors, and life support systems are functional. We need to explain how to develop user-defined components for tenant-specific functional requirements.>>

4.9 Logic Governing Function Assessment

<<Editorial note: This is a placeholder for the underlying logic in assigning the fragility damage state tags and consequences for function. This section may contain a short summary and a table, which describes the underlying logic in the component damage state assignments.>>

Chapter 5
Assessment of Recovery Time

5.1 Recovery Time

5.1.1 Overview

The building function assessment described above quantifies the level of function in the building based on the damage to each component and system within the building. However, the level of damage in a building is not static; as each component and system is repaired, the damage in the building is reduced, and the building regains function incrementally. To estimate the time until each component is repaired and building function is restored, a realistic representation of a building repair schedule, and the factors impeding the initiation of this repair schedule, is required.

The following sections discuss the quantification of impeding factors and the repair schedule used to estimate the repair times for damaged building systems. Quantification of component- and system-level repair times is used in conjunction with the building function assessment to develop recovery times for building reoccupancy and function, as shown in Figure 15.

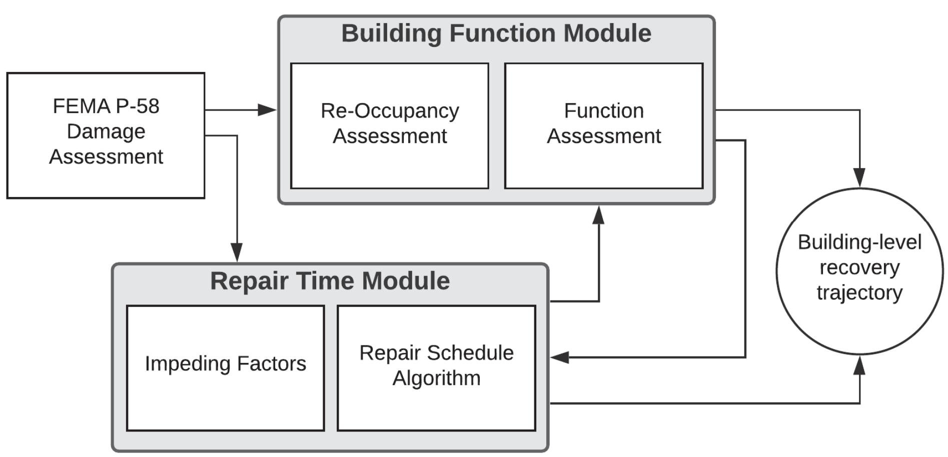

Figure 15 Overview of the integration between the repair time and building function module.

The methods discussed herein are conceptually adopted from previous work presented in REDi (2013), Yoo (2016), and Terzic (2020), but with significant differences in details of the structure and the adopted values. Other methods for estimating the repair schedule could be used. Important considerations include tracking the start and stop times for repairs to each of the individual building systems, addressing practical and common construction constraints, and consideration of factors that can delay the start of repairs.

5.2 Impeding Factors

<<Editorial note: The FRRC has yet to review impeding factors and additional input from cost estimators/building officials/contractors may be needed to confirm assumptions herein.>>

Impeding factors are those activities or factors that delay the *onset* of repair actions after an earthquake (e.g., REDi 2013, Terzic et al. 2020). These activities include building inspection, design and permitting, contractor mobilization, temporary clean-up and repairs, and other factors, as shown in Figure -16.

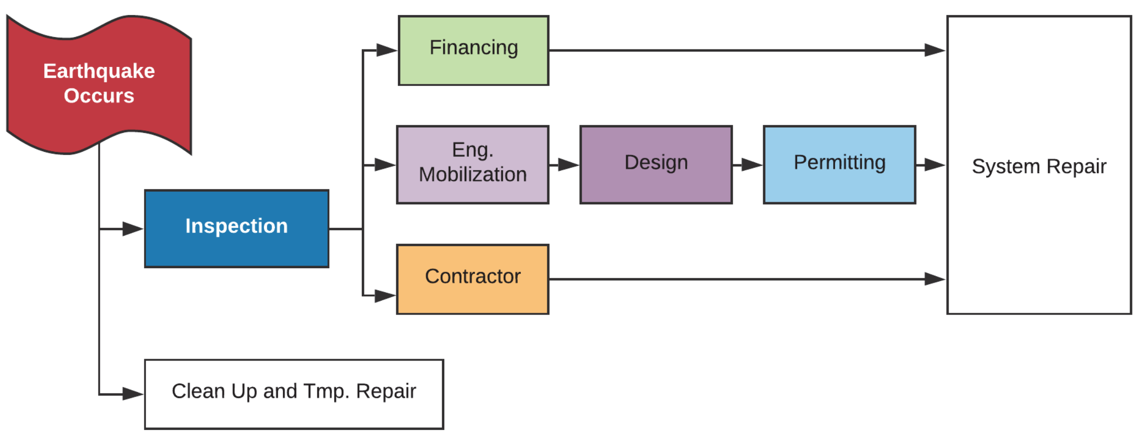

Figure -16 Flowchart showing the process to begin repairs after an earthquake and the factors that may impede the start of repair actions.

After an earthquake occurs, clean up and temporary repairs can occur immediately. Temporary repairs include removing, securing, bracing, and barricading of exterior and interior falling hazards, as well as boarding up of broken windows and damaged cladding components. Component damage that can be cleaned up or temporarily repaired has been discussed in previous sections and listed in the supplementary table titled FragilityDatabase_Function.csv.

Clean up (e.g., picking up falling ceiling tiles) and simple temporary repairs (e.g., unjamming a door) are assumed to take 3 days. Longer and more complicated repairs, such as shoring a local falling hazard, are assumed to take longer (7 or 14) days. Some damage, such as failures of exterior precast anchorages and widespread structural damage, cannot be temporarily repaired or cleaned up. The temporary repair times are inclusive of the time needed to find and mobilize a crew to conduct the temporary repair work. It is assumed that an owner can undertake these activities in parallel with an inspection. Temporary repair actions can mitigate the effect that damage has on reoccupancy or function, but do not change the subsequent time required to fully repair a damaged component or restore full functionality.

5.2.1 Inspection

Inspection times are assumed to be 3 days for essential facilities and 7 days for other buildings, as shown in Table 5. A building inspection is triggered if damage to any structural system at any story reaches 50% of the limits defined for a red tag (meaning, the number of components reaching the thresholds for Safety Classes 1, 2, and 3 limits is more than 0.5 times the number indicating designation of 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. The inspection time can be reduced to 1 day with the introduction of a Building Occupancy Resumption Program (BORP) or equivalent.

Table 5 Inspection Impeding Times

Condition	Mitigation Measure	System	Trigger	Median Impeding Time
Non-essential facility	--	All	50% of red tag threshold	1 week
Essential facility	--	“ ”	“ ”	3 days
All	BORB Equivalent	“ ”	“ ”	1 day

5.2.2 Financing

After inspection, financing, engineering design/mobilization and contractor mobilization can start concurrently. Financing time, summarized in Table 6, is required if the value of repairs needed exceeds the amount of immediately liquid-able funds, or cash-on-hand, available to the building owner. While this availability of funds will vary for different building owners, a cash-on-hand value of around 10% of the building replacement cost can be assumed for general cases.

Financing time scales with the cost of the repairs, relative to the owner's cash-on-hand, and depends on the type of financing being pursued. The distinction between financing options is similar to the structure proposed by REDi. Due to the long time taken to secure insurance payouts, the impeding time models assume that even those owners with insurance need to pursue private financing to conduct the repairs before the insurance payment is available.

Table 6 Financing Impeding Times

Condition	System	Trigger	Median Impeding Time	Min Time	Max Time
Pre-arranged credit	All	RC > CoH	1 week	--	--
Insurance	All	RC > CoH	Doesn't Control (see private loan time)	--	--
Private loans	All	RC > CoH	6*(RC - CoH) + 6 weeks	6 weeks	12 weeks
SBA-backed loans	All	RC > CoH	6 *(RC - CoH) + 6 months	6 months	12 months

RC: Building Repair Cost
CoH: Cash-on-Hand

<<Editorial note: This depends on the size of the loan and also the financial status of the owner. Most "Owners" don't own their building. The banks do. Thus, many Owners will have relatively little collateral. In many cases these times may be too short.>>

5.2.3 Engineering Mobilization and Design Time

Engineering mobilization and design time delays start of any repairs requiring redesign, including most structural repairs, as well as those to stairs and exteriors. 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 (engineering design time). A complete list of all component damage that requires engineering design is listed in the supplementary table titled FragilityDatabase_Impeding.csv.

Engineering mobilization times are required for any damage that requires redesign and are triggered based on the type of system that is damaged. If multiple systems require redesign, mobilization times are assumed to occur in parallel. Having an engineer on retainer is assumed to reduce these times, as shown in Table 7.

Table 7 Engineering Mobilization Time

Mitigation Measure	System	Trigger	Median Impeding Time
--	Structure	Triggered for this system if any system damage requires re-design	4 weeks
	Stair	" "	2 weeks
	Exterior	" "	2 weeks
Engineer on Retainer	Structure	" "	1 day
	Stair	" "	1 day
	Exterior	" "	1 day

The engineering system design time (SDT) is proportional to the repair time of the components within a given system, where the SDT is estimated as the sum of the worker days from the FEMA P-58 database for the damaged components requiring redesign. If multiple systems are damaged and need design, design times are assumed to occur in parallel, as shown in Table 8. An engineer on retainer does not reduce engineering design time.

Table 8. Engineering Design Time

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	" "	SDT	1 week	1 month
Exterior	" "	SDT	1 week	3 months

SDT: System Design Time

5.2.4 Permitting

Permitting is assumed to take place after engineering design and mobilization. Component repairs for which permitting is required, and the type of permit, are listed in Table 9. Two levels of permits are considered. Over-the-counter permits are for items that do not require significant review and are assumed to only take one day. Full review permits are for more heavily damaged systems that require more involved repair measures, such as damage to the structural systems or significant cladding or stair damage. Full permits review time (PRT) is assumed to be proportional to the repair time of the components that need review and is estimated as the sum of the worker days from the FEMA P-58 database for the damaged components whose design needs full permit review. Both over-the-counter and full review permits impede the start of repairs for any system that has damage requiring a permit.

Table 9 Permitting Impeding Times

System	Trigger	Median Impeding Time	Min Time	Max 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	4 weeks + PRT	4 weeks	16 weeks

PRT: Permit Review Time

5.2.5 Contractor Mobilization

Contractor mobilization times account for the time to arrange for a general contractor or subcontractors to conduct repairs, and time for those teams to arrive on site. Contractor mobilization times are listed in Table 10. Contractor mobilization is assumed to occur in parallel with financing and engineering design/mobilization. Contractor mobilization times are simulated independently for each building system (i.e., assuming the building owner will solicit an individual contractor for each building system, rather than one general contractor); mobilization times for each system are assumed to occur in parallel.

The time required to mobilize a contractor assumed to be proportional to the complexity of the repair job for a given system and is estimated as the system repair time (SRT) for which the contractor is being mobilized (where the system repair time accounts for worker allocations as discussed in the following section). Although these mobilization times are accounted for separately by system, the impeding time for any system is increased if there are many damaged systems, N_{DS}, indicating a more complex arrangement of teams needed to be on site. These times can be greatly reduced if a contractor is on retainer.

<<Editorial note: Contractors (and engineers) may be more likely to make themselves available for more complex (higher dollar value) jobs, thus reducing the mobilization time relative to less complex jobs.>>

Financing, engineering design/mobilization/permitting, and contractor mobilization are assumed to take place in parallel, as shown in Figure -16. The longest such sequence governs when repairs can begin. This delay is calculated on a system-by-system basis. For example, if design and permitting is not needed for electrical and plumbing repairs, those actions can take place before the design track has been completed.

<<Editorial note: It is possible for design to occur without financing; also design might need to occur before a contractor can bid, or before the level of financing needed can be known.>>

All impeding times are treated randomly, and uncertainty in these times are propagated through the Monte Carlo simulation in assessment of functional recovery times. Each time quantity is assumed to follow a truncated lognormal distribution, with median values as described in the tables above, and a lognormal standard deviation of 0.6, truncated at +/-2 standard deviations away from the mean. The maximum and minimum values listed in the tables above act as bonds on the estimated median impeding times, not on the simulated values.

<<Editorial note: We need to explain the truncation, why it is used here, and why it is not used elsewhere.>>

Table 10 Contractor Mobilization Impeding Times

Mitigation Measure	System	Trigger	Median Impeding Time	Min Time	Max Time
--	Structure	any damage	(1 + (NDS-1)/8) * SRT	4 weeks	12 months
	Stair	any damage	" "	2 week	6 months
	Exterior	any damage	" "	2 week	6 months
	Interior	any damage	" "	5 days	2 months
	Plumbing	any damage	" "	5 days	2 months
	Electrical	any damage	" "	5 days	2 months
	HVAC	any damage	" "	5 days	2 months
	Elevators	any damage	" "	5 days	2 months
	Fire Suppression	any damage	" "	5 days	2 months
Contractor on Retainer	Structure	any damage	0.5 * SRT	1 week	6 months
	Stair	any damage	" "	5 days	3 months
	Exterior	any damage	" "	5 days	3 months
	Interior	any damage	" "	1 day	1 month
	Plumbing	any damage	" "	1 day	1 month
	Electrical	any damage	" "	1 day	1 month
	HVAC	any damage	" "	1 day	1 month
	Elevators	any damage	" "	1 day	1 month
	Fire Suppression	any damage	" "	1 day	1 month

SRT: System Repair Time

These impeding factors do not include the effects of demand surge resulting from significant damage across a region that may delay inspections, permits, design and construction. In the current version, we also do not specifically account for long lead times on components, or time needed to procure/set up temporary elevators and cranes.

<<Editorial note: Omission of long lead times is a significant omission.>>

5.3 Repair Scheduling

<<Editorial note: updated repair scheduling should replace serial/parallel assumptions in FEMA P-58, and repair time should be defined as time to complete all repairs to full functionality.>>

A building repair schedule determines when the repair of each building system, and its constituent components, can occur, and is used to estimate how quickly reoccupancy or function can be restored or all repairs can be completed. As an update to the simplified serial and parallel estimates of building repair time presented in earlier versions of FEMA P-58, the repair scheduling algorithm in the functional recovery methodology develops a repair schedule for each realization of the Monte Carlo simulation that translates component-level repair times from the FEMA P-58 database (i.e., worker days) to building-level repair times in days, taking into the consideration worker allocations, construction constraints, delays in the start of repairs, and owner priorities. The goal of the updated repair schedule algorithm is to develop a reasonable estimate of repair time, but it is not intended to be a detailed virtual contracting system. The algorithm adopts much of the structure and worker assumptions contained in Yoo (2016), with modifications to repair constraints, prioritization, and optimization.

The repair schedule accounts for critical construction constraints and details, breaking down repairs by system, and scheduling crews for each of the damaged building system based on the assumed available workers and prioritization of repairs. An overview of the repair schedule algorithm logic is illustrated in Figure 17.

Based on the available workers, the repair schedule algorithm assigns repairs to damaged components, beginning with the highest priority system in the first story. The number of workers assigned to the repair of each component are based on assumptions about crew numbers and crew sizes for different building systems and trades (Yoo, 2016), as discussed below. If there are available workers in a story or building level, the algorithm assigns crews to repair the most highly prioritized system in other stories and, subsequently, to other systems based on priority. Workers are allocated to repairs until a construction constraint or maximum worker limit is reached. If worker limits are exceeded at a story level, but building worker limits are not exceeded, workers are assigned to conduct repairs in additional stories in parallel. Additional crews and repairs must wait until there are enough available workers space within the building to begin repairs, representing bottleneck and float items in an actual repair schedule. Once workers finish with a system, space becomes available for additional workers to be allocated to other unrepaired systems in the building until all systems are fully repaired.

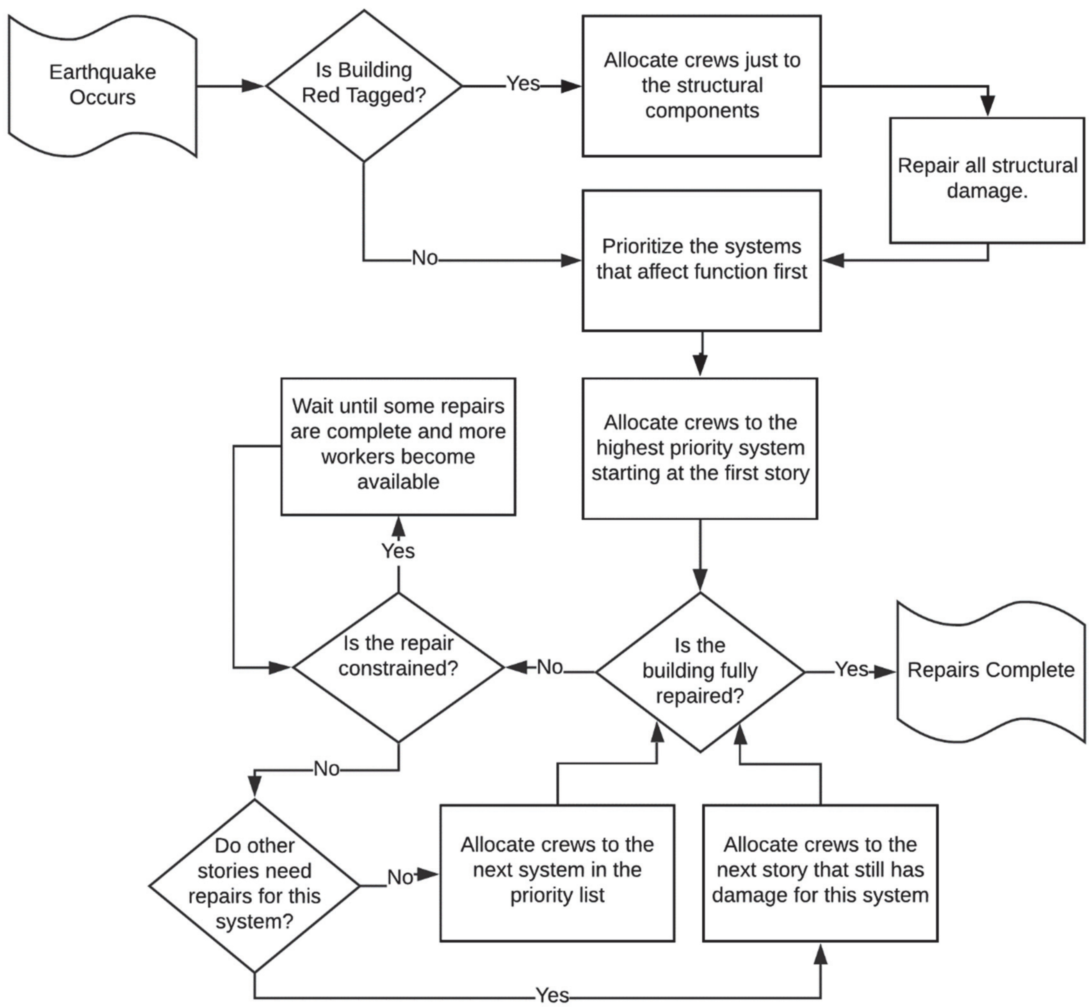

Figure 17 Flowchart illustrating the proposed repair schedule algorithm.

5.3.1 Prioritization of Repairs for Recovery of Function

The repair schedule algorithm assumes that an owner and contractor will prioritize restoration of function where practical, meaning actions that will restore function are taken first unless there is some logical construction constraint that would prevent this (e.g., partitions would never be fully repaired before the structure in the same story, but partition damage would be cleaned up if that would restore function). Each building system is assigned a default repair prioritization, provided in Table 11. However, this list is adjusted and systems whose damage is not impairing function are moved down the list, based on the damaged components in a particular realization. Systems that are prioritized for affecting function maintain their same relative priority with other systems that also affect function. Repair priorities must still meet all construction constraints.

Table 11 Default Prioritization of Building Systems in Repair Schedules

System ID	System	Default Repair Priority
1	Structural	1
2	Exterior Enclosure	5
3	Interior Components	9
4	Stairs and Doors	2
5	Elevators	7
6	Water/Plumbing	3
7	Electrical/Power	4
8	Heating Ventilation and Air Conditioning (HVAC)	6
9	Fire Suppression	8

5.3.2 Worker Allocations

Worker crew sizes and allocations are reported in Table 12, based primarily on information from Yoo (2016), which was based on interviews with contractors in California. For each building system, required crew sizes for various components are determined based on the severity of component damage (average damage state per story), and the number of crews is based on the number of damaged components. The required crew sizes for each damage state are provided in the supplementary table titled FragilityDatabase_CrewSize.csv. When assigning crews to repair system damage, the number of crews assigned will fluctuate depending on worker limitations and construction constraints. However, the crew sizes for various types of damage will always remain constant (i.e., a single worker will not be assigned to a job that requires two).

Table 12 Default number of crews assigned for each building system

System ID	System	Number of Damaged Units per Crew	Max Number of Crews Per Component Type
1	Structural	10	10
2	Exterior Enclosure	10	2
3	Interior Components	All	1
4	Stairs and Doors	All	1
5	Elevators	All	1
6	Water/Plumbing	All	1
7	Electrical/Power	All	1
8	Heating Ventilation and Air Conditioning (HVAC)	All	1
9	Fire Suppression	All	1

5.3.3 Construction Constraints

The repair scheduling algorithm considers limitation based on the maximum workers in a given story, maximum workers on site (i.e., for the whole building), and construction sequence constraints. Workers are limited to 1 worker per 1000 sq. ft. at any given story (FEMA P-58), and limited to between 20 and 260 workers on the site, depending on the size of the structure (REDi, 2013). Other than worker limits, there are no restrictions placed on how many stories can be repaired at once.

Among the sequence constraints, the repair scheduling algorithm assumes that interior finishes at a particular story are never repaired before structural components at the same story, even if interior finishes are affecting function and would otherwise be "prioritized" for repair. Additionally, if the structure receives an unsafe placard (is red tagged), structural components must be repaired first, starting in the bottom story, until all structural components are repaired in the entire building. Structural repairs among multiple stories can occur in parallel, as long as worker limitations are satisfied.

5.3.4 Repair Schedule Uncertainty

To calculate time to restore function and to fully repair the building, the repair schedule is calculated for each realization. An example is shown in Figure 18. 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 fragility database. Uncertainties in the prioritization scheme are not considered.

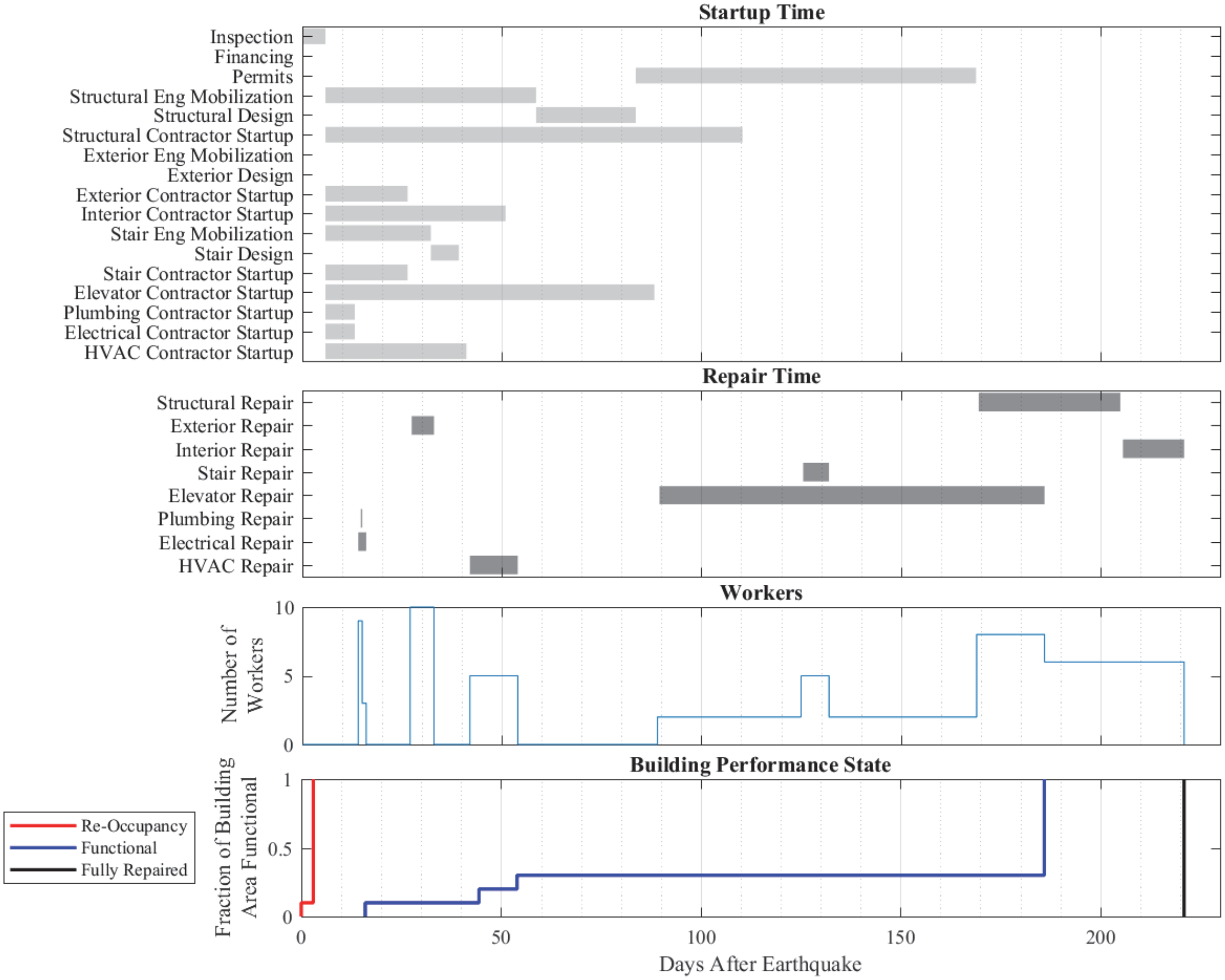

Figure 18 Example impeding times, repair schedule, worker allocations, and recovery trajectories for a single realization of the functional recovery assessment.

5.4 Recovery Time for Full Functionality

Full functionality is a recovery state that is achieved when all damaged components within the building are repaired. The recovery time for full functionality is the repair time necessary to complete all repairs, considering impeding factors and repair scheduling described in the preceding sections.

The full functionality recovery state is quantified at the building-level, rather than the tenant-unit level, as it is a property of the building rather than the tenant occupancy or tenant function.

<<Editorial note: we will need to discuss potential future impacts on functionality when permanent repairs are made to replace temporary repairs; including assumptions about repairs in an occupied building.>>

Appendix A
Supplementary Fragility Database Tables

A.1 Fragility Database Tables

Much of the quantification of building reoccupancy and function depends on consequences of component specific damage. Not all damage to structural components is a safety issue. Similarly, not all HVAC system damage will fail the system or cause loss of function. Therefore, in the definition of a building component fragility specification, additional consequences that define the effect of each damage state on reoccupancy, function, and recovery time are needed.

The provided data tables in the attached Supplementary Tables directory define the component damage state consequences for unsafe placards (FragilityDatabase_UnsafePlacards.csv), building reoccupancy and function (FragilityDatabase_Function.csv), impeding factors (FragilityDatabase_Impeding.csv), and worker limitations (FragilityDatabase_CrewSize.csv), for each of the FEMA P-58 building components. Each table is used to augment the existing FEMA P-58 fragility database. Components or damage states that are absent from the provided tables are assumed to have no additional consequences related to reoccupancy or function.

<<Editorial note: we will need to decide how to present the various functional recovery spreadsheets (e.g., narrative description in report; more detailed information in an appendix, and then full information in its entirety as part of the supporting electronic materials in FEMA P-58, Volume 3)>>