Method for Probabilistic Evaluation of Post-Earthquake Functionality of Building Systems

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ABSTRACT

Recent large earthquakes have caused significant building damage resulting in lengthy functional recovery times. Post-earthquake recovery time can be minimized through improved design of building systems essential for providing continuous operation. This study presents a novel method for probabilistic evaluation of the post-earthquake building’s functionality to support functionality-based seismic design. Aligned with the PBEE methodology, the proposed method utilizes FEMA P-58 damage assessment results in conjunction with fault trees of complex building systems to find the percent of building area with compromised functionality and to identify building components that impair its functionality. The primary user-defined inputs are probabilistic limit state functions of individual building components, which define the damage thresholds for partial (local) and full loss of the building functionality. The proposed method is highly flexible; it has a modular structure that allows easy extension by adding new features. A case study is conducted for an existing 13-story building to demonstrate the functionality evaluation and showcase how its results can guide the retrofit measures for improved seismic performance.

Keywords: recovery, fault tree analysis, PBEE, contributors to impaired functionality

1. INTRODUCTION

Major earthquakes repetitively cause huge disturbance to struck areas by damaging infrastructure which in turn results in significant economic losses and major social disruption. As evidenced by M8.8 27 February 2010 Chile earthquake, a great number of buildings experienced considerable damage, causing building closures and as a result significant indirect loss (lost product and income) (Miranda et al, 2012; EERI, 2010). Furthermore, Toyoda (2008) showed that in the Kobe Earthquake of 1995 the contribution of both direct loss (cost of repairs) and indirect loss to the total capital loss of the stricken area were significant and equally important. Furthermore, his
research showed that lost productivity or income in terms of estimated indirect losses continued to rise for more than 10 years. To assure quick post-earthquake recovery, building systems essential for providing continued functionality can be protected through improved building design (Terzic & Mahin, 2017).

The Performance-Based Earthquake Evaluation (PBEE) methodology developed by the Pacific Earthquake Engineering Research (PEER) Center provides a probabilistic framework for performance assessment and design of buildings utilizing performance objectives meaningful to decision-makers, stakeholders, and insurers (e.g., repair cost, repair time). Recently, Federal Emergency Management Agency [FEMA] P-58 initiative (FEMA, 2018a; FEMA, 2018b) adopted PBEE for general use by developing a comprehensive library of peer-reviewed fragility curves and associated consequence functions considering more than 700 structural and nonstructural building components. The first step in this methodology is selection of ground motion records representative of excitations expected at the site. The ground motions are typically selected to represent different levels of earthquake hazard, ranging from low to high. For each hazard level, the selected ground motion records are used in conjunction with dynamic analysis software and appropriately selected numerical models to simulate the range of structural responses. Furthermore, engineering demand parameters (EDPs) are selected for all components of the system and related by components’ fragility curves (cumulative exceedance probability distributions of corresponding EDPs) to their damage measures/states (DMs) (e.g., local beam flange buckling, broken windows) to evaluate possible damage conditions of the building. These DMs are used in conjunction with components’ consequence functions to estimate the corresponding earthquake losses or damage consequences (e.g., components’ repair costs, components’ repair time, etc.). Finally, the component losses are used to evaluate the total
earthquake losses (e.g., total repair cost, total repair time). These earthquake losses are known as decision variables (DVs), which provide valuable information for stakeholders upon which informed design decisions can be made. The primary DVs considered in FEMA P-58 focus on a total repair costs and a crude estimate of a total repair time. Although the methodology represents a significant step forward towards quantifying earthquake-induced losses, it lacks models for evaluation of building functional recovery that is necessary for the evaluation of downtime and indirect losses.

In 2015, Burton et al. have proposed a framework for incorporating PBEE in the assessment of seismic resilience of residential communities, where the functional recovery of individual single-family residential buildings was evaluated by incorporating limit states defined by SPUR (Poland et al. 2009). The study has established general definitions for limits states necessary for evaluation of functional recovery and has provided their formulation for simple single-family residential buildings. For complex building systems, Porter & Ramer (2012) and Jacques et al. (2014) have demonstrated that fault-tree analysis (FTA) can be effectively used to evaluate the risk of losing functionality. In these studies, FTA is used to relate the functionality of complex building systems to the state of the subsystems and its components. Jacques et al. (2014) applied the FTA method to deterministically assess the “reduction in functionality” and “complete loss of functionality” of critical hospital services due to earthquake damage. To validate the fault-tree model, they used field data from the 2011 Christchurch Earthquake and reported a mixed level of success in capturing all that occurred after an earthquake. While the method was successful in estimating the functionality of most hospital services, it failed to accurately estimate the functionality of few services due to the lack of a dynamic aspect in the fault-tree structure. Porter and Ramer (2012) applied FTA to a computer data center to
characterize the risk of losing functionality due to earthquake damage. The example analysis by Porter and Ramer (2012) was validated by several means: a red-team exercise, comparison with generic judgment-based standards, comparison with the actual earthquake performance history of the facilities, and comparison with their own judgment and that of the facility operators; reasonable agreement between analysis and observations was reported.

A building-level method for evaluating post-earthquake functionality (i.e., the percent of usable area within a building) is essential for the proper estimation of its recovery process (Cimellaro et al., 2010; Burton et al., 2015; Terzic et al, 2016; Mieler et al. 2018, Sun et al. 2019). This study presents a novel method for probabilistic evaluation of building’s post-earthquake functionality, which relies on generating functionality limit state for a particular earthquake scenario as a probability that “x” percent loss in building functionality will be reached (where “x” is any number between 0 and 100). Within the context of this study, the functionality loss represents a percent of the inaccessible functional area within a building. The proposed method uses FEMA P-58 damage assessment results in conjunction with a fault tree of a complex building system to generate building’s functionality limit state and to identify components that impair its functionality. The primary user-defined inputs are probabilistic limit state functions of individual building components, which define the damage thresholds for partial (local) and full loss of the building functionality. The presented method is applicable to the cases when a building is owned by a single entity, however, the method is highly robust and flexible, and can be extended to include cases when the building is owned by multiple entities. The flexibility and robustness of the proposed method are demonstrated on an existing 13-story office building described by Garza et al. (2018) and its functionality-based results are used to showcase how they can guide the retrofit measures for improved seismic performance.
2. METHOD FOR EVALUATING POST-EARTHQUAKE FUNCTIONALITY

To facilitate the development of the building-level probabilistic functionality limit state (FLS) for a particular seismic hazard, which is used to evaluate building’s post-earthquake functionality, the study proposes a fault-tree for a complex building system. The fault-tree is derived from interviews with facility managers and published work (Porter & Ramer 2012; Jacques et al 2014; Johnson et al 1999; Pate-Cornell 1984; Vesely et al 1981; and Prassinos et al 1986) and is used in conjunction with information about structural and nonstructural damage that can impair building function to determine the percent of the area within a building with restricted access. The information about damage states of building components is acquired from FEMA P-58 performance building analysis. To enable calculation of the FLS, the method utilizes user-defined limit state functions (LSFs) that define the damage thresholds for partial (local) and full loss of building functionality. The proposed method is created with the following goals in mind: 1) flexibility; branches in the fault trees can be easily turned ON and OFF, 2) robustness; the method has a modular structure allowing for effortless expansion by adding new features, and 3) speed of evaluation; work-flows between structural analysis, damage analysis, and post-earthquake functionality analysis can be created to allow rapid evaluation of building’s functionality.

2.1 Generic Fault Tree of the Complex Building System

A generic fault tree that relates the functionality of a complex building system to the state of its subsystems is shown in Figure 1. The top event is associated with the percent loss of building functionality and lower events represent the percent loss of function of its subsystems. Note that the term “Fails” in the figure means either full or partial loss in building functionality as damage can fully or partially (locally) impair the building function. Lower events are represented by
subsystems critical for maintaining the basic building function and include the core building systems (electrical power system, HVAC system, piping system, vertical transportation system, architectural systems, and structural system) as well as the lifeline and other systems (e.g., utility systems, critical building equipment, staff, and supplies). Each subsystem is related to the top event through an ‘or’ gate, indicating that the reduced functionality of any of the lower events reduces the functionality of the top event. Furthermore, each subsystem has its own fault tree that relates the functionality of the subsystem to the damage state of its components (these fault trees are presented in Section 2.3). It is to be noted that the great majority of residential and office multi-story buildings mostly comprise of these core subsystems, providing the broad application for the main developments presented in this paper. While the presented study does not provide detailed information on building-specific and lifeline systems, these can be adopted from other studies (e.g., Porter & Ramer 2012 and Jacques et al 2014) and accounted for by adding additional branches to the fault tree presented in Figure 1. Additionally, each of the subsystems presented in Figure 1, can be turned off from the fault tree if not applicable to the building of interest.

**FIGURE 1.** Generic fault tree for a complex building system.
2.2 Step-by-Step Procedure for Establishing the Functionality Limit State

In line with FEMA P-58 methodology, the proposed method utilizes information on damage states of all building components generated through the Monte Carlo process, which evaluates building performance for a large number (hundreds to thousands) of realizations to explore the effect of uncertainty on the predicted outcome. For each realization of the Monte Carlo simulation process, which represents one possible damage state of the building, the loss of functionality for the entire building (assuming that the building is owned by a single entity) is expressed with one of the three outcomes:

1. **0% loss of functionality;** when all building subsystems are fully functional.
2. **X% (partial) loss of functionality (0 < X <100);** when a function of some of the subsystems is compromised. Partial loss of functionality applies to cases when damage to the subsystems are localized, restricting access to the areas in the building affected by the damage while the rest of the building remains open and functional.
3. **100% loss of functionality;** when any of the critical subsystems fail.

The functionality outcomes from all realizations are ordered from smallest to largest to construct a post-earthquake functionality limit state, which is expressed as a probability that “x” percent loss in functionality will be reached. The high-level procedure for the development of this limit state is next described and is supplemented by the low-level procedures pertinent to specificities of the core-building subsystems (described in Section 2.3).

To derive the functionality limit state for the building system, functionality of all subsystems is first evaluated at every floor of the building utilizing their fault trees, where each subsystem comprises of components whose damage can reduce the subsystem’s capacity to function (their fault trees are provided in Section 2.3). Loss in functionality from all subsystems
is then utilized to calculate the loss in functionality of the entire building system (per the method described in this section). Figure 2 provides a flowchart that illustrates the process for evaluating the loss in building’s functionality for every realization of the FEMA P-58 performance assessment simulation. The process initiates by the acquisition of data from existing FEMA P-58 performance model and analysis results, it is followed by user-defined inputs (i.e., LSFs), and is finalized with the calculation of the loss in system functionality; the entire process is next described in detail.

Step 1: Acquire data from FEMA P-58 performance model and isolate components that can impair functionality. The first step of the proposed method is acquiring fragility IDs from an existing FEMA P-58 performance model and identifying those building components that can impair the functionality of their subsystems. Furthermore, damage states of each selected fragility are evaluated to recognize those that can influence functionality. For example, lower damage states of many building components are associated with minor or cosmetic damage that does not impact functionality; as such, these damage states are not considered in functionality calculations.

Step 2: Group fragility IDs by component type and calculate group quantities. Components that can impair functionality are grouped by component type. In FEMA P-58 performance model, multiple fragility IDs of the same component type can occur. For example, several fragilities representing moment connections of different sizes and joint types (e.g., beams on two sides of the joint or beam from one side only) may be present in the performance model of the building. For the purpose of evaluating post-earthquake functionality, they will be grouped together and assigned to, for example, the “moment connections” component type. Note that the
FIGURE 2. Flowchart for evaluating the loss in functionality for one realization for the entire building.

- **Step 1**: Identify building components and their damage states that can impair functionality.
- **Step 2**: Group fragility IDs by component type.
- **Step 3**: Set their limit state functions to establish the extent of damage that triggers partial and full loss of function.
- **Step 4**: Find number of damaged units for every DS that can impair functionality, per comp. type.
- **Step 5**: Determine damage state ratios of components:
  \[
  \text{dmg ratio,}_i = \frac{\text{number of damaged units within DS}_i}{\text{total number of units}}
  \]
- **Step 6**: Any critical component triggered full loss?
- **Step 7**: Loss in functionality is calculated for every subsystem.
grouping of fragility IDs should apply only to those component types where grouped fragilities have similar implications on the loss in functionality of the subsystem. Moreover, each component type might have multiple groups; for each floor and for the entire building (referred to as component groups). Finally, the total quantities (i.e., number of units) of a component type will be calculated for all of its groups as applicable (per floor and for the entire building) utilizing information extracted from the FEMA P-58 performance model.

**Step 3: Set user-defined inputs.** To calculate the functionality limit state of a subsystem, each component of a subsystem is defined with the limit state functions (LSFs) that define the extent of component damage to trigger either partial (local) or full interruption of subsystem function. Given that many of building subsystems can preserve its full function with some damage to its components, LSFs for partial interruption of function are very important as they set the threshold for the acceptable extent of the damage. Additionally, each LSF should receive a tag that specifies whether the functionality is impaired immediately or only during the actual repair. This information is used to properly evaluate the consequences of the incurred damage. For example, if the incurred damage of a component type only impairs functionality during the actual repair, it will not have an effect on the post-earthquake building functionality but will have an effect on the recovery process as a whole.

LSFs are lognormal distributions, defined with their medians and dispersions, for every damage state of a component type that can impair functionality (provided by a user; unique to a project). Furthermore, if a component is located only at one level of the building (e.g., cooling tower, located at the roof level), its LSFs are defined as ratios of damaged components, with respect to its total quantity, required to trigger partial and full interruption of the subsystem.
function. For components distributed throughout the building (e.g., shear tabs, located at every
floor), two types of LSFs must be defined:

1) *Floor-based LSFs:* expressed with ratios of damaged components within a floor along
   with a number of floors with such damage necessary to trigger full and partial loss of
   subsystem function (an example is provided in Table 1);

2) *Building-based LSFs:* expressed as ratios of damaged components within the entire
   building to trigger partial and full loss of subsystem function (an example is provided
   in Table 1).

These two types of LSFs for the distributed components allow consideration of the effects of
their local (floor-based) and overall (building-based) damage on functionality. They are used one
at a time to evaluate the functionality of a subsystem, where the highest loss in functionality
between the two results is the final result of the subsystem. Please note that for taller buildings,
certain extent of component damage has to be exceeded across several floors to compromise its
functionality, and therefore, *floor-based LSFs* are defined with two parameters, damage ratio
threshold for a floor and a number of floors where damage needs to exceed the threshold to
compromise functionality. Table 1 shows an example of user-defined inputs for limit state
functions for a building component that is located at every floor. Note that the presented example
only serves for illustrative purposes, where provided medians and dispersions of LSFs may not
be realistic.
Table 1. Limit State Functions for the Component Damage States as Defined in FEMA P-58

| Component type | DS # | DS description | Building-based LSFs | Floor-based LSFs |
|----------------|------|----------------|---------------------|------------------|
|                |      |                | Partial loss LSF    | Full loss LSF    |
|                |      |                | No. of stories      | LSF              | No. of stories |
| Shear tabs     | 2    | Partial tearing of shear tab and possibility of bolt shear failure (6-bolt or deeper connections) | *0.1 (M) 0.3 (D) | *0.15 (M) 0.3 (D) | 5 | 0.3 (M) 0.3 (D) | 3 |
|                | 3    | Complete separation of shear tab, close to complete loss of vertical load resistance | 0.05 (M) 0.3 (D) | 0.15 (M) 0.3 (D) | 5 | 0.15 (M) 0.3 (D) | 3 |

DS: damage state; M: median; D: dispersion; LSF: limit state function
* Functionality affected only during the actual repair

**Step 4: Acquire the number of damaged units from FEMA P-58 analysis results.**

FEMA P-58 analysis results are next utilized to extract the number of damaged units (i.e. quantity) for each damage state that can impair functionality, and their quantities are aggregated per component type. This information is then used to find ratios of damaged components (designated as dmg ratio in Figure 2) for every damage state of interest. These damage state ratios are calculated by dividing the number of damaged units in the damage state of interest by the total number of units in the group. Multiple damage state ratios are obtained for each damage state of a component type; one for the entire building and one for every individual floor when applicable.

It is to be noted that in some cases there may be a need for introducing an aggregate damage ratio that is a weighted combination of considered damage ratios for a component type. Considering the example of shear tabs presented in Table 1, it is clear that the full loss of functionality will be triggered if there is more than 10% of the shear tabs in the building that have experienced the full tearing (DS3), but it may also be reasonable to trigger the full loss of functionality if 8% of shear tabs have full tearing (DS3) and 15% of shear tabs have partial tearing (DS2). To capture such cases, an aggregate damage ratio (ADR) can be defined as:
\[ ADR = \sum_{i}^{n} W_i DR_i, \] where \( i \) is the damage state number, \( W_i \) is the weight assigned to damage state \( i \) (user-defined input, where \( \sum_{i}^{n} W_i = 1 \)), and \( DR_i \) is the ratio of units in damage state \( i \). In cases when an aggregate damage ratio is used, the weights associated with different damage states along with the corresponding LSF shall be defined in Step 3, along with all other user defined parameters. For example, if a user assigns weights of 0.4 for DS2 and 0.6 for DS3 of shear tabs and defines full-loss LSF with a median of 0.1, then for a case of 15% shear tabs in DS2 and 8% of shear tabs in DS3 the \[ ADR = 0.4 \cdot 0.15 + 0.6 \cdot 0.08 = 0.108, \] which exceeds the median limit state threshold of 0.1, and may therefore result in the full loss of functionality.

**Step 5: Calculate functionality tags for all component types.** To initiate the calculation of the post-earthquake functionality of the building, functionality tags are first established for all component types. Based on the amount and severity of damage, three tags can be assigned: 1) no loss in functionality, 2) partial loss in functionality, and 3) full loss in functionality.

To assign the tag to a component type, damage state ratios of its groups (per floor and for the building) are used together with LSFs of associated damage states to determine if the component group has the potential to trigger reduction of subsystem functionality. To keep the method probabilistic, a random number generator is used to determine if the functionality limit state threshold for a component is exceeded for the considered realization. For each group, the damage state ratio of a component type is compared with the threshold for triggering the full loss of functionality. If the threshold is exceeded, the group receives a ‘full loss of functionality’ tag. Otherwise, the damage state ratio of a component type is compared with the threshold for triggering partial loss of functionality. The resulting group tag, in this case, can either be ‘partial loss’ (if the threshold is exceeded) or ‘no loss in function’ (if the threshold is not exceeded). This information is next used to generate two functionality tags: building-based and floor-based.
While the building-based functionality tag of the considered component type directly corresponds to its group that represents the entire building, the floor-based tag is calculated using tags of individual floors in conjunction with the number of damaged floors required to trigger the reduction of functionality. If the number of floors with ‘full loss of functionality’ tag for floors exceeds the threshold, the floor-based tag is ‘full loss of functionality’. Otherwise, the number of floors with an aggregate of full and partial loss of functionality tags is compared with the threshold. The resulting floor-based tag will be either ‘partial loss of functionality’ if the threshold is exceeded or ‘no loss of functionality’ if it was not. Finally, the building-based tag and the floor-based tag are compared and the tag representing the higher loss of functionality is assigned to the considered component type.

**Step 6: Calculate the loss of functionality for every subsystem.** With functionality tags assigned to all component types, it is proceeded with the calculation of the functionality loss of a subsystem. This calculation process is unique for each subsystem and is based on the logic of the subsystem’s fault tree. While the fault trees for all subsystems and calculation of partial loss in their functionality is presented in detail in Section 2.3, the general procedure is presented here.

In general, if any critical component of a subsystem (those connected to the upper event in the fault tree with an ‘or’ gate) receives a ‘full loss of functionality’ tag, subsystem functionality loss is 100%. Otherwise, the subsystem fault tree logic is used to calculate the loss of functionality if one of the following two outcomes is realized: 1) the highest tag among subsystem components is ‘partial loss of functionality’, or 2) there is at least one component connected to the upper event with an ‘and’ gate that receives ‘full loss of functionality’ tag. Finally, if all component types within a subsystem receive ‘no loss of functionality’ tag, subsystem functionality loss is 0%. 
When a subsystem causes partial loss of building functionality for a considered realization, an analysis is conducted for each floor to calculate the percent area of the floor with compromised/lost function. The subsystem loss of function for the entire building is then calculated as the weighted average loss in functionality from all floors. The loss in functionality of a subsystem calculated for all realizations is next used to develop a functionality limit state for the subsystem.

**Step 7: Calculate the loss of functionality for the entire building system and create a functionality limit state.** With a loss in functionality evaluated for each subsystem at every floor of the building, it is to be proceeded with the calculation of the loss of functionality for the entire building system. The loss of building functionality is expressed with one of the three outcomes: 1) no loss of functionality; if all building subsystems are fully functional, 2) partial loss of functionality; when the function of some of the subsystems is compromised, and 3) full (100%) loss of functionality; if any of the critical subsystems fail.

When partial loss of functionality is observed, two models are considered: 1) **common area model**, which assumes that damage to different subsystems affects the same area within a floor and 2) **complementary area model**, which assumes that damage to different subsystems affects different floor areas, which do not overlap. These assumptions are necessary as FEMA P-58 procedure does not provide information about the location of damaged components within a floor. While neither model is accurate, they bound the estimate of the partial loss of building functionality. While in the case of the common area model, the maximum loss in functionality from all subsystems at one floor is announced the loss in functionality for that floor, the complementary model calculates the loss of floor functionality as the sum of functionality losses from all subsystems at the floor, not to exceed 100%. The loss of functionality for the entire
building system is then calculated as the average loss in functionality among all floors considering both, common and complementary area models. Finally, the functionality outcomes from all realizations of the Monte Carlo simulation process are ordered from smallest to largest to construct post-earthquake functionality limit state, which is expressed as a probability that “x” percent loss in building functionality will be reached. If excessive, the partial functionality outcomes for a building can also be used to trigger the full loss of functionality (e.g., loss of building function of 80% may result in the full building closure).

2.3 Building Subsystems Fault Trees

Each of the core building subsystems has its own fault tree that relates the functionality of a subsystem to the damage states of its components. Note that while a complete procedure for calculating loss in functionality of a subsystem is presented in Section 2.2, this section presents fault tree logics for all core building subsystem and provides a method that shall be used to calculate the partial loss of functionality if one of the following two outcomes is realized: 1) the highest tag among subsystem components is ‘partial loss of functionality’, or 2) there is at least one component connected to the upper event with an ‘and’ gate that receives ‘full loss of functionality’ tag.

When evaluating the functionality of building subsystems, it is important to account for interdependencies among different subsystems. For example, the functionality of the HVAC system depends on available electrical power supply and functional motor control centers, which distribute the power to the HVAC equipment. Furthermore, electrical power available for HVAC components depends on the functionality of the elevator system as the total power has to be shared between elevators and HVAC equipment. To account for interdependencies among
subsystems, the fault trees of core building subsystems are next presented in the order in which they have to be evaluated to properly account for the interdependencies.

**Structural System.** Figure 3 shows the fault tree for a structural system. For this tree, branches include structural component groups that can affect reduction or loss of building functionality (e.g., moment connections of the steel moment frame can be assigned to Group 1), as well as consideration of excessive residual drifts and collapse. Different buildings comprise of different component types that provide resistance to gravity and lateral loads and may therefore have a different number of groups/branches in the tree.

![Fault tree for a structural system](image)

**FIGURE 3. Fault tree for a structural system.**

If any of the structural component groups triggers full loss of function, which is directly related to the trigger of unsafe placard due to structural damage, the subsystem will have a full loss of function. If partial loss of functionality is triggered for one or more component groups, the percent loss in functionality is then approximated as the sum of ratios of damaged components among component groups. For example, if at a considered floor 20% of moment connections and 15% of shear tabs trigger partial loss of functionality, loss in functionality for the subsystem at that floor is 35% (20% + 15%). This method assumes that damage to different component groups affects different areas of the building, possibly overestimating the affected area that loses functionality, therefore representing an upper bound for the loss in function of the
structural subsystem. More accurate methods for evaluation of the partial functionality loss as a result of damage to different components of the structural system should be further investigated.

**Electrical Power System.** The fault tree for the system that provides the electrical power consists of the components presented in Figure 4. The purpose of the power system is to distribute and control power throughout the building. The power system in a building depends on utilities or backup systems to supply electricity and components necessary for the power distribution (e.g., low voltage switchgear, distribution panels). While every multi-story building has low voltage switchgear and power distribution panels; backup system, transformers, and control panels may not be present, and in such a case should be turned off from the fault tree.

FIGURE 4. Electrical power system fault tree.
If all components of the power distribution system fail, the entire power system fails. Otherwise, if the power supply system is functional but the functionality of some components of the power distribution system is compromised the power system may have partial functionality. In this case, the remaining functionality depends on the configuration of the building distribution system and must be modeled accounting for its specificities. For example, if switchgear is located at every floor of a 10-story building, and are dysfunctional only at one floor, assuming no damage to other components of the power distribution system, 10% of the power will be lost. However, if switchgear is located at every other floor, distributing power over two floors, their failure at one floor results in a 20% loss in power for the building.

The backup power system typically provides power from a centralized location and is more likely to be present in buildings with critical functions, such as IT buildings (critical for communications) and hospitals (Joshua Cichuniec, personal communication, January 22, 2019). The capacity of power supplied to the building would depend on the type of generators in the building, often providing the only partial supply of power. For power to be generated, all components of the system must function, including generators, batteries, battery racks, and power control systems. In case of failure of any of the subsystem components, the functionality is fully compromised.

**Stair and Elevator Systems.** The fault trees for stairs and elevators are presented in Figure 5. Stairs and elevators are critical for providing vertical transportation routes through the building. The stairs represented in the fault tree are emergency stairs used for egress points and elevators represented in the fault tree are the minimum number of elevators needed to maintain the building’s functionality after an earthquake. Two fault trees are presented to distinguish between the buildings that have different functional requirements for stairs and elevators. If the
building is low- to mid-rise, both the emergency stairs and elevators are required to fail for the system to fail (Figure 5a). We are assuming that if only elevators fail, emergency stairs will be used to provide the basic building function, and if only emergency stairs fail, elevators will be used to maintain basic building functions. For high-rise buildings, we are assuming that elevators and stairs must both be functional at the same time to provide the basic building function (Figure 5b). For high-rise buildings, elevators are critical for the mobility of occupants (and if needed for transportation of construction materials and workers), while emergency stairs are required for egress ways for the safety of occupants in case of fire. In the presented fault tree, the set number of stories, \( x \), that separates two presented scenarios must be decided by the user based on the specificities of the considered building.
FIGURE 5. Elevator and stair system fault tree.

The level of damage to stairs and elevators that triggers their loss of function is associated with the unsafe condition. For example, damage to stairs that causes loss of their live load capacity results in loss of their function. Any damage to elevators that are beyond cosmetic damage and pose a safety hazard to users would require the elevator to be shut down (Joshua Cichuniec, personal communication, January 22, 2019). Furthermore, even if elevators are functional, the motor control centers (MCC) failure or power supply failure will also cause the elevators to be out of operation. However, if the elevators have access to a backup electrical system, they may be functional even in the case of electrical utilities failure (Mahdi
If the backup electrical system is not present or does not feed into the elevator system, it should be turned off from the fault tree.

When there is no damage to the electrical system, but elevators and/or stairs receive a tag for partial loss in functionality, the elevator and stair system have partial functionality. In the case of low- to mid-rise buildings, where both elevators and stairs are regularly used, the loss in functionality is calculated as the ratio of the number of total stair and elevator units that are no longer functional to the total number of stairs and elevators in the building. For high-rise buildings, where elevators are the primary and dominant way of transportation, the loss in functionality is equal to the percentage of elevators that are no longer functional. However, if the electrical system has reduced capacity due to damage to MMCs, providing insufficient power for running operational elevators, the functionality of the elevator/stair system will be further reduced. In this case, the total loss in functionality of the elevator/stair system will depend on the emergency plan for the building as the available power has to be distributed among all building equipment.

**Plumbing and Piping Systems.** The fault tree for plumbing and piping systems consists of the components presented in Figure 6. The purpose of the plumbing and piping system is to distribute water and other required fluids to specific parts of the building. Cold and hot potable piping typically service restrooms and sinks, heating hot water and chilled water piping distribute water from heating and chilling systems to HVAC systems or sinks and fountains, sanitary waste piping distributes waste from restrooms or sinks to sewage systems, steam piping distributes steam typically for laboratory spaces or hospitals, and fire sprinkler piping and fire sprinkler drops provide and dispense water as a fire safety system.
FIGURE 6. Plumbing and piping system fault tree.

Components critical to the system are cold or hot potable piping, heating hot water piping, chilled water piping, sanitary waste piping, and steam piping (when present within a building). Major leakage from any of these pipes that cannot be contained or isolated can result in overall system failure and building shutdown by facilities manager or other building officials (Joshua Cichuniec, personal communication, February 4, 2019).

Noncritical components include fire sprinkler piping and fire sprinkler drops. These components are part of a building’s fire safety system, but if damaged do not stop fire safety systems from operating (Joshua Cichuniec, personal communication, February 4, 2019). If fire sprinklers and drops are out of function but the rest of a building is functional, it is possible for facilities staff to conduct “fire watch” by regular building inspection for fires while fire sprinkler systems are undergoing repair. If facility managers have the aforementioned protocol in place the fire sprinkler system can be turned off from the fault tree, otherwise it will be turned on.

Partial functionality can occur with the piping system if the effects of the piping damage can be contained within an area of the building. Minor leakage and brace failure can occur with
any critical piping, resulting in a local shutdown of the affected space in the building, including the area where the leakage occurs and the rooms that are serviced by these piping. The percentage of piping that is no longer functional represents a partial loss in functionality for the piping system.

Special instances and considerations in the piping system include automatic shut off sensors and battery backup systems. There can be cases where specific piping is supported by earthquake valves that shut down at an entry point in the system (Joshua Cichuniec, personal communication, February 4, 2019). Leak detection can also support piping but may not have the capability to shut down leaking pipes, only to alert building operators of the leaks.

**HVAC Systems.** The fault tree for HVAC systems consists of the components presented in Figure 7. The primary purpose of the HVAC system is to provide ventilation, and the secondary purpose is to provide air conditioning and heating if needed or desired. Air handling units (AHUs) supply air and exhaust, cooling towers support chillers in providing cool air to AHUs, boilers provide warm air to AHUs, HVAC ducting supplies air to the building’s zones or designated spaces, and the electrical system consisting of motor control centers (MCC) and power supply system provides power to the HVAC equipment (Joshua Cichuniec, personal communication, January 22, 2019; Predrag Nikolic, personal communication, September 10, 2019). Note that power supply components are presented earlier as a part of the fault tree of the power system (see Figure 4). Once evaluated as a part of the power systems, the generated information about the available power supply are used within the fault tree for the HVAC system. Lastly, while some facility managers may keep the building occupiable as long as ventilation is provided, others may also require air conditioning and/or heating. For this reason,
heating and cooling systems can be turned on and off from the fault tree to accommodate different conditions.

FIGURE 7. HVAC system fault tree.

While cooling is often considered a luxury, in some instances it may be critical for preserving the building’s functionality. Some examples include buildings dedicated to telecommunication equipment, laboratory spaces with special chemicals and equipment, weather conditions that affect the temperature in a building to a level that prevents occupants from using the building. Similarly, the heating system might be necessary for preserving the building function in the case of extreme cold weather. Furthermore, for spaces with critical equipment, HVAC systems are often supported by backup generators to prevent loss of power supply by utilities from shutting down critical equipment in these spaces.
Figure 8 shows the flowchart for calculation of the post-earthquake functionality of the HVAC subsystem when the entire building is airconditioned or heated for the case when cooling or heating systems are turned ON. The presented flowchart can be easily extended to account for other scenarios where only portions of the building are airconditioned or heated.

FIGURE 8. Flowchart for calculation of functionality of the HVAC system.

Following the logic of the HVAC system fault tree (Figure 7) and the presented flowchart (Figure 8), we see that if any critical component of the HVAC system fails, the entire HVAC system fails. Otherwise, if some components of the HVAC system have compromised functionality, the HVAC system may have partial functionality. This is possible since HVAC components are typically separated by the sections of the building they service, or by “zones”. Assuming that all “zones” cover an approximately equal amount of space within a building, we can then calculate partial functionality of AHUs as the fraction of the AHUs that are still functional. Furthermore, for every functional AHU, it will be checked if corresponding HVAC ducting is functional. If HVAC ducting of a functional AHU has failed, the corresponding
“zone” can not be ventilated, and therefore, the functionality of the air handling system is further reduced.

If the cooling system is necessary for the building functionality and chilled water piping is functional, the cooling system’s remaining post-earthquake capacity will be the smaller of the following: the ratio of functional chillers and ratio of functional cooling towers. Similarly, in the case when the heating system is needed to preserve the building’s functionality, the heating system’s partial functionality is equal to the ratio of functional boilers (assuming functional heating hot water piping). If the electric power is not compromised, the partial functionality of the HVAC system is then smaller of the air handling system functionality and cooling/heating system functionality. In addition to calculating total HVAC system functionality, functional “zones” within a building are identified and used to evaluate the functionality of individual floors.

Next, we will consider the case where the electrical system has reduced functionality. If utilities do not provide power, the HVAC system can not operate. However, if utilities provide power but MMCs experience damage that reduces the functionality of the electrical system (e.g., 50% of units dysfunctional), the total power they provide must be split between elevators and HVAC units. Depending on the primary building function, building facility managers will have an emergency plan in place to decide how to distribute the power. For instance, their priority may be an emergency elevator that requires 20% of the total power provided by MCC, which is an input for the algorithm presented in Figure 8. If there is no damage to mechanical components of the elevator and power is supplied either by utilities or backup system, 20% of the power provided by MCCs is allocated to the elevator. The remaining 30% is then used for the HVAC units based on priorities. However, if the elevator has mechanical damage, the full 50% of the
remaining power goes to HVAC units. Note that the information about number of functional elevators and the power that they require to maintain their function has been evaluated as a part of stairs & elevator subsystem and utilized when analyzing HVAC system. If the functional HVAC units need less power than what is available, the functionality of the HVAC system is unchanged from what was previously calculated. However, if HVAC units need more power than what is available, the functionality of the HVAC system is equal to the percentage of available power.

**Partition Wall Systems.** Partition wall systems only consist of partition walls themselves. The purpose of partition wall systems is to provide privacy or separate areas within a building. Generally, partitions are considered cosmetic to the building space except for areas where privacy is essential (Joshua Cichuniec, personal communication, February 4, 2019). If there are utilities in a partition wall and the wall is damaged, such as cracking in a wall exposing piping or electrical conduits, this can pose a hazard to occupants and result in local space being shut down. Significant quantities of partition walls with warping, splitting, or cracking can also indicate damage to the structural system, to where the building must be shut down until confirmation of no structural damage to the building is received or repair is completed. Damage to partition walls can result in the partial and full loss of functionality to a building since partition wall damage can allude to potential damage to other subsystems. If the partial loss is triggered, the percent loss in functionality for partition walls is the percent of all partition walls that are severely damaged.

**Exterior Wall Systems.** The fault tree for the exterior wall system consists of cladding and curtain wall components, as seen in Figure 9. The critical purpose of exterior walls is to protect the interior building space and occupants from the outside elements.
Both types of components are critical to the exterior wall system. If a building contains both cladding and curtain walls, both are required to have full functionality for the building to allow any occupancy. Similar to partition walls, extensive damage to cladding and curtain walls can hint to the damage of the structural system. If a significant amount of damage such as cracking or warping is observed by facilities management, the building will be shut down until a lack of structural damage is found or damage is repaired (Joshua Cichuniec, personal communication, February 4, 2019).

The partial functionality of exterior wall systems is possible. The ratio of damaged exterior components is the loss in partial functionality of the system. This would represent the scenario where exterior damage is localized and only affected spaces of the building are closed.

**Ceiling Systems.** The fault tree for the ceiling system consists only of ceilings themselves. The main purpose of ceiling systems is to hide building infrastructure, including piping, electrical wiring, and ducting. While components of the ceiling system are not critical for maintaining the building function, fallen ceiling tiles can hint damage to other systems that are located above the ceiling, along with possibly making the floor unsafe or unoccupiable due to the fallen debris or failure of the ceiling grid system (Joshua Cichuniec, personal communication, February 4, 2019). If significant ceiling damage is found after an earthquake, inspection is required before allowing occupancy, resulting in loss of functionality for the building.
If damage to the ceiling system is localized, the building will have partial loss of functionality, which is calculated as the ratio of the damaged ceiling at a floor, therefore restricting the closure only to the affected building spaces.

3. DEMONSTRATION OF THE PROPOSED METHOD: A CASE STUDY

The building selected for demonstration of the presented method for evaluation of post-earthquake functionality is a 13-story steel-framed building located in downtown Los Angeles (California) built circa 1956. A recent study by Garza et al. (2018) provides a detailed description of the building and presents a performance assessment of the building in terms of repair loss and repair time considering three levels of earthquake hazard: 50% in 50 years, 10% in 50 years, and 2% in 50 years.

The building considered in this study has a typical column layout of 6.1m – 7.1m (20’ – 23’3”) on center within a building footprint of 26.4m (86’8”) by 48.8m (160’). It is framed with wide-flanged columns in each direction, and wide flanged beams typically spaced 2.0m (6’8”) on center, supporting a 38mm (1½-inch) deep metal deck with concrete fill for a total slab thickness of 95mm (3¾ inches). Unlike typical steel moment frames, this building used relatively shallow beam sections that constitute a moment connection at every beam-to-column joint in both directions. Hence there are many weak-axis moment-connections in this building that do not conform to the current building code requirements.

A comprehensive 3D nonlinear model of the building was developed in OpenSees (McKenna, 2004) to simulate earthquake responses of the building for the sets of twenty pairs of horizontal ground motion records, one set for each of the considered hazard levels. The structural analysis results were incorporated into the performance model of the building, developed in PACT (FEMA, 2018b), which included appropriate fragilities for all structural,
architectural, and MEP components of the building. Monte Carlo simulation process, implemented in PACT, utilized 2000 realizations for each hazard level to probabilistically simulate the possible range of building damage. This study utilizes the information on building damage to evaluate the functionality limit states for each building subsystem and the entire building.

As explained earlier, the three main constituents necessary for the calculation of functionality limit states are damage assessment results from FEMA-58 analysis, fault trees of the building and its subsystems, and limit state functions of building components that probabilistically define a threshold for the extent of damage to be exceeded to impair building function (partially and fully). This example utilizes fault trees defined in Section 2, damage assessment results from FEMA P-58 analysis of the 13-story building, and limit state ratios (user-defined input) of building components as specified in Table 2. The tabulated data present the specific components of the building subsystems along with their functionally impairing damage states, and corresponding medians of their LSFs for the purpose of the building-based and floor-based analysis; all LSFs have a dispersion of 0.3. It is important to note that these LSFs are selected only for the purpose of demonstrating the proposed method for evaluating post-earthquake functionality (presented in Section 2.). To provide the content to the case study, LSFs were selected based on recommendations from facility managers and structural engineers. However, this selection is based on a limited set of collected information and is not intended for wide application until verified.
Table 2. Limit State Functions for the Component Damage States for the 13-Story Building

| Component Type         | DS # | DS description                                                                 | Building-based LSFs | Floor-based LSFs |
|------------------------|------|--------------------------------------------------------------------------------|---------------------|------------------|
|                        |      |                                                                                  | Partial loss        | Full loss         |
|                        |      |                                                                                  | LSF No. of stories  | No. of stories    |
| **Column Splices**     | 2    | DS1 followed by complete failure of the web splice plate and dislocation of the two column segments on either side of the splice. | 0.01 0.02           | 0.01 1           |
|                        | 1    | Fracture of upper or lower beam flange weld.                                   | 0.20 0.50           | 0.30 4           |
|                        | 2    | Similar to DS1, except fracture propagates into column flanges.                 | 0.20 0.50           | 0.30 4           |
|                        | 3    | Fracture initiating at weld access hole and propagating through beam flange, possibly accompanied by local buckling deformations of web and flange. | 0.10 0.25           | 0.15 4           |
| **Pre-Northridge Moment Connections** |      |                                                                                  |                      |                  |
| Curtain Walls          | 2,3  | Glass falls from frame                                                           | 0.05 0.5            | 0.1 7           |
| Cold Form Exterior Walls | 2  | Buckling of steel sheathing. Buckling of framing members.                        | 0.05 0.5            | 0.1 7           |
| **Partition Wall Subsystem** |      |                                                                                  |                      |                  |
| Partition Walls        | 3    | Buckling of studs and tearing of tracks. Tearing or bending of top track, tearing at corners with transverse walls, large gap openings, walls displaced. | 0.05 0.7            | 0.1 7           |
| **Stair & Elevator Subsystems** |      |                                                                                  |                      |                  |
| Stairs                 | 3    | Loss of live load capacity. Connection and or weld fracture                      | 0.2 0.75            | 0.25 4           |
| Traction Elevators     | 1-1  | Controller anchorage failed, and or machine anchorage failed, and or motor generator anchorage failed, and or governor anchorage failed, and or rope guard failures. | 0.01 1              | n/a n/a
|                        | 1-2  | Rail distortion, and or intermediate bracket separate and spread, and or counterweight bracket break or bend, and or car bracket break or bend, and or car guide shoes damaged, and or counterweight guide shoes damaged, and or counterweight frame distortion, and or tail sheave dislodged and/or twisted. | 0.01 1              | n/a n/a
|                        | 1-3  | Cab stabilizers bent, or cab walls damaged, or cab doors damaged.                | 0.01 1              | n/a n/a
| Motor Control Center   | 1    | Damaged, inoperative.                                                            | 0.01 1              | n/a n/a
| **Ceiling Subsystem**  |      |                                                                                  |                      |                  |
| Suspended Ceilings     | 2    | 50% of ceiling damage                                                            | 0.1 0.75            | 0.15 7           |
|                        | 3    | 50% of ceiling damage                                                            | 0.05 0.5            | 0.1 7           |
| **Piping Subsystem**   |      |                                                                                  |                      |                  |
| All piping (w/o sanitary) | 2  | Large Leakage w/ major repair - 1 leak per 1000 feet of pipe                        | 0.05 0.1            | 0.075 4          |
| Sanitary piping        | 2    | Large Leakage w/ major repair - 1 leak per 1000 feet of pipe                        | 0.02 0.05           | 0.02 4           |
| **Electrical Subsystem** |      |                                                                                  |                      |                  |
| Low Voltage Switchgear | 1    | Damaged, inoperative.                                                            | 0.1 0.75            | 0.15 7           |
| **HVAC Subsystem**     |      |                                                                                  |                      |                  |
| AHU                    | 1-1  | Equipment does not function. Damage to attached ducting or piping.               | 0.01 1.0            | n/a n/a
| HVAC Ducting           | 2    | Several adjacent supports fail and sections of ducting fall - 60 feet of ducting fail and fall per 1000 foot of ducting. | 0.1 0.75            | 0.15 7           |
| Motor Control Center   | 1    | Damaged, inoperative.                                                            | 0.01 1.0            | n/a n/a

DS: damage state; LSF: limit state function
For each subsystem and the entire building, Figure 10 presents probabilities of each of the functionality states (no loss, partial loss, and full loss of functionality) for the three considered hazard levels (50% in 50 years, 10% in 50 years, and 2% in 50 years). The results suggest a high probability of attaining the partial loss of functionality for a building at frequent earthquakes (50% in 50 years). For rare and very rare earthquakes (10% in 50 years, and 2% in 50 years), the building will most certainly have a full loss of functionality. When the functionality of the core subsystems is observed, we see that the HVAC subsystem has the strongest influence on the building’s functionality. It is accompanied by stair & elevator, piping, and structural subsystems, especially at higher hazard levels. The results further show that there is a high certainty that the partition walls, exterior walls, ceiling, and electrical subsystem, will be fully functional for frequent earthquakes and might have compromised function for rare and very rare earthquakes.

Finally, Figure 11 shows functionality limit states for every subsystem and the entire building, which show probability that “x” percent loss in subsystem/building functionality will be reached for each of the three considered hazard levels. For example, the median value of functionality loss (reduction of the usable area) for a building at frequent earthquakes is 50%. For rare and very rare earthquakes, the median value of the building’s loss of functionality is 100%. Again, we see that the functionality limit states for the building are primarily governed by the HVAC subsystem. Furthermore, contributions of the building subsystems to its functionality loss are as follows: 1) for frequent earthquakes, median values for loss of functionality are 0% for all subsystems, except for HVAC and stair & elevator subsystems, which are 50% and 20%, respectively; 2) for rare earthquakes, median values for loss of functionality are 0% for the ceiling, exterior wall, and electrical subsystem, while they are 2% for piping, 13% for partition
walls, 27% for the structural system, 80% for stairs and elevators, and 100% for HVAC; 3) for very rare earthquakes, median values of loss of functionality are 0% for the ceiling, 15% for the electrical subsystem, 35% for exterior and partition walls, and 100% for structural, piping, HVAC, and stairs and elevator subsystems.

FIGURE 10. Probability of functionality states (no loss, partial loss, and full loss of functionality) for the building system and its subsystems at three considered hazard levels.
FIGURE 11. Functionality limit states for the building system and its subsystems at three considered hazard levels.

The presented case study demonstrates the unique capability of the presented method to generate probabilistic post-earthquake functionality limit states of a building for a selected set of hazard levels. With the proposed method, the building’s functionality is not crudely evaluated in a binary mode (full loss or no loss) but rather as a probability that “x” percent loss of building functionality will be reached (where “x” is any number between 0 and 100). These functionality
limit states (as presented in Figure 11) can be compared to functionality-based performance objectives (i.e., acceptance criteria) set by decision-makers to check whether the building has acceptable performance. For example, for a frequent earthquake, the analyzed building with its median functionality loss of 50% greatly exceeds a typical performance objective of close to full functionality, indicating a need for a building retrofit.

Furthermore, the case study demonstrates the capacity of the proposed method to isolate contributors (i.e., subsystems) to interrupted building operation, which is essential in guiding the development of earthquake mitigation strategies and design/retrofit solutions for improved seismic performance. In case of the considered building, it is clear that the structure, HVAC system, elevators, and piping need to be retrofitted to improve post-earthquake functionality across all hazard levels. For example, the employment of dampers within the building, along with the equipment anchorage and replacement of elevators and piping could greatly improve the post-earthquake functionality of the building. Finally, it is important to note that this knowledge about building components that impair building function is essential for the evaluation of the entire recovery process for a building.

In sum, the presented method is readily applicable to individual buildings, as user-defined data (LSFs) can be uniquely defined for every project by collecting the appropriate data from the building’s facility manager and structural engineers. However, to provide broad research application of the presented method, an effort needs to be made towards creating generic sets of probabilistic limit state functions (where applicable) of damage thresholds with the goal of evaluating not only the functionality of individual buildings but rather clusters of buildings and their effects on community resilience.

4. SUMMARY AND CONCLUSIONS
This study proposes a novel method for evaluating a building’s post-earthquake functionality, which relies on generating a functionality limit state for a particular earthquake scenario as a probability that “x” percent loss in building functionality will be reached (where “x” is any number between 0 and 100). The method recognizes full and zero loss of the building functionality, as well as any intermediate state, in which case, the loss of functionality is restricted to limited areas within the building. The proposed procedure for the development of a functionality limit state assumes that the analyzed building is owned by a single entity, however, it can be further extended to address the cases when the building is owned by multiple entities, therefore consisting of functionally independent spaces. Three main sets of data necessary for the development of the functionality limit state are: 1) damage assessment results from FEMA-58 analysis, 2) fault trees of the building and its subsystems (provided in this study), and 3) limit state functions of building components that probabilistically define a threshold for the extent of damage to be exceeded to impair building function (partially and fully); uniquely defined for every project. The proposed method is developed with the following goals in mind: 1) flexibility; branches in the fault trees can be easily turned ON and OFF, 2) robustness; the method has a modular structure allowing for an effortless extension by adding new features, and 3) speed of evaluation; work-flows between structural analysis, damage analysis, and post-earthquake functionality analysis can be created to allow rapid evaluation of building’s functionality. Given the presented method attributes, it is obvious that the method can be used for the functionality-based analysis of any building type and size. Finally, the case study of an existing 13-story building is conducted to demonstrate functionality evaluation with the proposed method and to showcase how the method can be used to isolate the building contributors (i.e., subsystems) to interrupted functionality and use them to propose retrofit measures for improved seismic performance.
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