Multi-scale earthquake impacts: A review of the state-of-the-art in modeling loss of functionality in buildings

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Abstract

Earthquake-induced damage to the built infrastructure can generate enormous societal impact, ranging from displacement of individual families and businesses to disruption of entire economic sectors and public services. Consequently, engineers play a critical role in mitigating these cascading, multi-scale earthquake impacts. A significant component in this effort involves designing buildings and other structures to avoid the types of damage that can lead to loss of functionality and downtime after an earthquake. Towards this end, this paper describes the state-of-the-art in assessing earthquake-induced loss of functionality in individual buildings. More specifically, it details how earthquake-induced loss of functionality within the built infrastructure can generate multi-scale impacts that cascade through a community across space and time. It also proposes a consistent hierarchy of definitions for building functionality and examines the myriad combinations of events and failures that can impact it, culminating with the development of functionality restoration curves that graphically depict how the availability of various building components and systems affect the recovery of functionality. The paper then reviews both recently developed analytical models for evaluating loss of functionality in individual buildings and also current practice for designing buildings to maintain or regain functionality after earthquakes. Lastly, the paper identifies several critical gaps in knowledge and areas of future research that need to be addressed in order for the engineering profession to more effectively design buildings to regain functionality soon after a major earthquake.

Keywords: functionality; downtime; buildings; infrastructure

1. Introduction

While the field of disaster resilience has received considerable attention from researchers and practitioners over the past two decades, the findings from this important field have been slow to translate into engineering practice. Clearly, engineers have an important role to play in enhancing the resilience of communities to disasters. The built infrastructure – which includes buildings, lifeline systems, and other engineered structures – provides the physical foundations for most economic, social, and cultural activities that take place within a community [1]. As recent earthquakes in Chile, New Zealand, and Japan have illustrated, damage to the built infrastructure can cause not only casualties and economic losses, it also can impact the availability of important community services, including housing [2, 3], sanitation [4, 5], healthcare [6–8], education [3, 9], and public transit. Therefore, a crucial component in the effort to enhance community resilience involves improving the seismic performance of the built infrastructure.

More specifically, improving the seismic performance of the built infrastructure translates into maintaining functionality across different scales of infrastructure following a disaster, from structural and nonstructural components within an individual building to regional networks of facilities and lifeline systems, all of which work together to support important community services. Historically, the building codes and engineering standards that govern the design, analysis, and construction of the built infrastructure in the United States and other countries have focused on protecting life safety, not preventing loss of functionality, except for a small subset of facilities with critical post-earthquake functions (e.g., hospitals, police and fire stations, emergency operations centers). While these codes and standards have proven effective at reducing casualties in major earthquakes, they have been less successful at preventing the type of damage that can impact building functionality. Consequently, a specific component in the effort to improve the performance of the built infrastructure involves designing most buildings to regain functionality soon after a major earthquake.

However, maintaining functionality in a building involves a distinct set of challenges above and beyond protecting life safety. Towards this end, this paper describes the state-of-the-art in modeling earthquake-induced loss of functionality in individual buildings. It begins by introducing the concept of multi-scale earthquake impacts – a concept that captures how earthquake-induced loss of functionality within the built infrastructure affects communities across multiple scales, including space and time. Next, the paper proposes a consistent hierarchy of definitions for building functionality and examines the myriad combinations of events and failures that can impact it. This discussion culminates with the development of functionality restoration curves that graphically depict how the availability of various building components and systems affects the recovery of functionality. The paper then reviews both recently developed analytical models for evaluating loss of functionality in individual buildings and also current practice for designing buildings to maintain or regain functionality after earthquakes. Lastly, the paper identifies several critical gaps in knowledge and areas of future research that need to be addressed in order for the engineering profession to more effectively design buildings to regain functionality soon after a major earthquake.

2. Multi-scale earthquake impacts

A community is an entity with geographic boundaries and shared fate that comprises natural, built, and human infrastructures that influence each other in complex ways [10]. The natural infrastructure refers to the surroundings or conditions in which a community exists, and comprises hydrologic, geologic, atmospheric, and biologic features that can enrich, protect, or potentially threaten a community (e.g., rivers, oceans, mountains, basins, wetlands, faults, climate, watersheds, vegetation, etc.). The built infrastructure includes any physical structure or feature built by humans, including buildings, lifeline systems, and other engineered structures (e.g., hospitals, schools, homes, power grids, roads, bridges, etc.). Human infrastructure comprises individuals and groups of people, both formal and informal (e.g., families, businesses, governments, economic sectors, etc.).

These three infrastructures work together through a complex network of interactions to enable and support normal community functioning, including a wide range of economic, social, cultural, and religious activities and exchanges. Natural hazards such as earthquakes, hurricanes, and floods can damage a community's built infrastructure, which in turn can disrupt the normal functioning of a community. For example, when an earthquake occurs near a community, it triggers ground shaking and other hazards that can alter the natural infrastructure and cause damage to the built infrastructure. Damage to the built infrastructure, in turn, can unleash an additional set of hazards, including fire following earthquake, inundation from dam failure, and release of hazardous materials, which can cause further damage to the built infrastructure. This primary and secondary damage gives rise to *multi-scale impacts* that can cascade through a community. Multi-scale impacts are referred to as such because they evolve across space and time. Some examples include:

- Physical, emotional, and/or psychological trauma to individuals
- Displacement of families from their homes and students from their schools
- Permanent outmigration of families and businesses
- Loss of functionality in buildings and lifeline systems (including cascading loss of functionality caused by interdependencies)
- Disruption to the operations of individual organizations, businesses, and institutions
- Disruption of important community services and/or economic sectors
- Economic losses for individuals, families, organizations, businesses, and institutions

Multi-scale impacts cascade through a community via interactions within and across the three infrastructures. For example, an otherwise undamaged building may be rendered unusable if important utilities are unavailable after an earthquake. Similarly, a business in an undamaged building with full access to utilities still may be impacted if its suppliers' operations are disrupted. Consequently, these interactions give multi-scale impacts a degree of nonlinearity, where damage to individual components within the built infrastructure can, when aggregated, result in disproportionate consequences for a community. This paper focuses on a small but important piece within this broader framework: functionality of individual buildings and facilities.

3. Definitions of functionality

In the most general sense, functionality refers to the availability of a building or facility to be used for its intended purpose. Most crucially, this definition does not conflate damage to and/or failure of building systems and components with the impact it has on the human infrastructure (e.g., availability of hospital services, continuity of business operations, etc.). Instead, functionality refers simply to whether a building can be used in a normal capacity. Consequently, the concept of functionality is rooted firmly in the built infrastructure, and can be thought of as an intrinsic characteristic or attribute of a building. However, the specific requirements for maintaining functionality in a building after an earthquake depend on the individual or organization that occupies the structure. For example, doctors and nurses will have a different set of functional requirements for a hospital than workers in an office building. In a hospital, cracking of interior partitions might render a surgical space unusable, whereas in an office building this type of damage is unlikely to affect functionality (though it will still need to be repaired, which could be disruptive). The proposed definition of functionality is flexible enough to handle these variations (i.e., "used for its intended purpose"). Table 1 defines several different levels of functionality, ranging from none to full. Each functionality level corresponds to a unique combination of building placard (obtained from an ATC-20 post earthquake safety evaluation) and utility availability. For example, the "baseline" functionality level results if a building receives an inspected placard (i.e., green tag) and has access to critical utilities, where critical utilities refer to the minimum set of utilities required by a particular building occupant.

As a consequence of this definition, downtime will refer the duration of time required to restore functionality to a building. Because functionality is defined on a discrete scale ranging from none to full, downtime can be used to measure the time to restore varying levels of functionality to a building. Similar to functionality, the concept of downtime is rooted firmly in the built infrastructure, as it measures the duration of time that a building's functionality is impacted. However, it can be strongly influenced by events and factors within the human infrastructure, as discussed in the next section.

Table 1 – Levels of functionality corresponding to different combinations of placard and utility availability

Functionality level	ATC-20 placard	Utilities	Damage	Description
None	None (not yet inspected)	Not applicable*	Potentially significant	The building has not been inspected, but has been damaged and evacuated
Restricted entry	Unsafe (red)	Not applicable*	Significant, requiring repair or demolition	The building is not safe to occupy or enter, except as authorized by the local jurisdiction
Restricted use	Restricted use (yellow)	Not applicable*	Moderate to significant, requiring repair	Parts of the building are not safe to enter or occupy
Re-occupancy	Inspected (green)	Unavailable	Minor, requiring repair	The building is safe to occupy but does not have access to utilities
Baseline	Inspected (green)	Critical ones available	Cosmetic, requiring repair	The building is safe to occupy and has access to critical utilities
Full	Inspected (green)	All available	None	The building is safe to occupy and has access to all utilities

* Availability of utilities is not applicable as the building cannot be entered or occupied

4. Causes of loss of functionality

Informed by data collected following past earthquakes, researchers have identified a diverse set of events and factors that can impact building functionality, many stemming from earthquake-induced damage to internal systems and components. In general, a building can lose functionality if its safety, serviceability, or accessibility is compromised. A building is safe if it does not pose undue risk to its occupants and the surrounding environment. More specifically, it has adequate margin to resist loads associated with normal use (i.e., dead and live load), and also has the capacity to withstand aftershocks and other transient loads (e.g., wind, snow, etc.). Furthermore, important life-safety services are available within the building, including fire detection and suppression and emergency evacuation and egress. Similarly, a building is serviceable if its physical spaces are usable and important building services are available, including lighting and power, water, HVAC, and communications. Building services can be compromised by either internal building damage or loss of supply from external utility providers. Finally, access to a building may be compromised if it is threatened by damage to adjacent structures or landscapes, or is located within a cordon zone.

Fig. 1 presents a fault tree that generically captures the set of events and failures that commonly lead to loss of functionality after an earthquake. A fault tree is an analytical model that graphically depicts the logical combinations of faults and failures that can lead to an undesired state for a particular system or component [11]. Thus, fault trees provide a compelling framework for developing specific relationships between damage to or unavailability of the myriad building systems and components, both internal and external, and the overall impact on building functionality. The top event in Fig. 1 represents loss of building functionality. Beneath this top event are six high-level intermediate events: fire safety compromised, structural integrity compromised, weather tightness compromised, building services compromised, usable space compromised, and neighborhood compromised. These six events are connected to the top event through an OR-gate, meaning that the occurrence of any one of these six events will result in loss of functionality for the building. The first two high-level intermediate events in Fig. 1 primarily impact the safety of the building, while the next three events largely affect its serviceability. All six events, however, are rooted in the built infrastructure (i.e., they all result from physical damage to either the building itself or nearby structures).

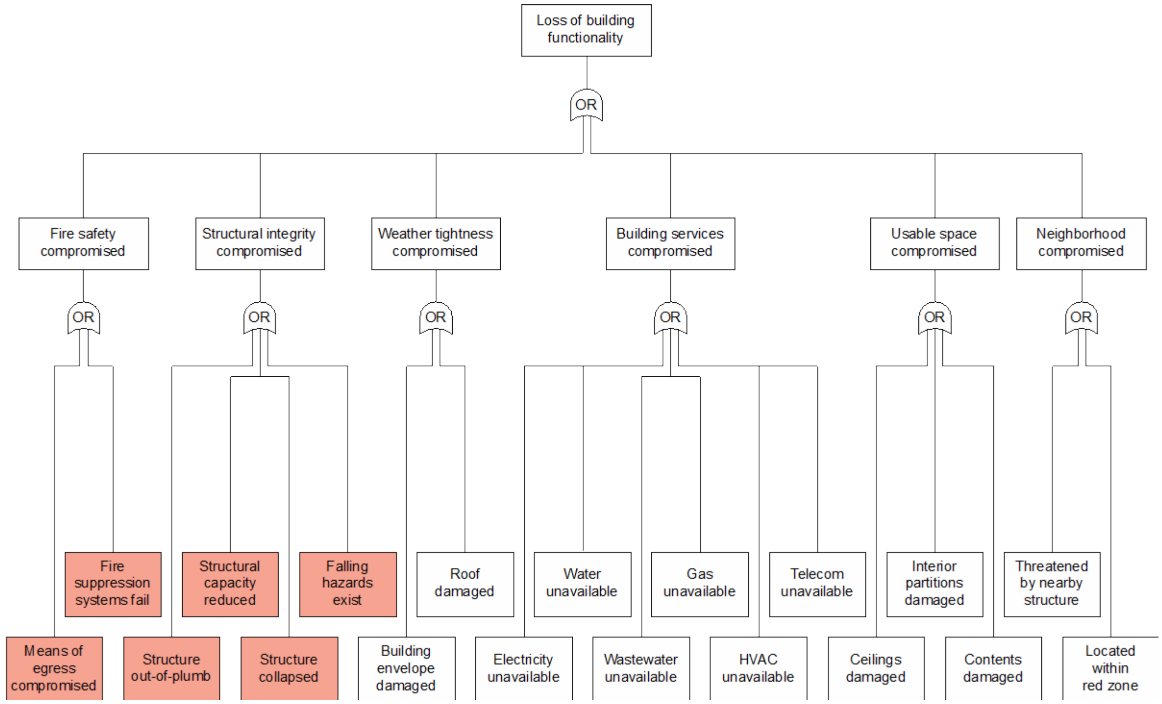

Fig. 1 – Fault tree for capturing events that commonly cause loss of functionality in buildings.

The structure and logic of the fault tree in Fig. 1 is such that the occurrence of any of the 19 events at the bottom of the tree will render the building unusable, highlighting the fact that a large number of factors can affect building functionality after an earthquake. A closer inspection of each event, however, reveals that different events can have profoundly different impact on other dimensions of building performance, including safety, repair costs, and downtime. For example, the event “Structure out-of-plumb” will undoubtedly result in lengthier downtime and higher repair costs than the event “HVAC unavailable.” Furthermore, certain events can result in a building receiving an unsafe or restricted use placard after an earthquake, resulting in forcible closure of the building, loss of functionality, and potentially significant periods of downtime. These events, which are shaded red in Fig. 1, correspond to specific items on an ATC-20 post-earthquake safety evaluation form that can trigger an unsafe or restricted use placard. In contrast, other events may impact a limited portion of a building, resulting in loss of functionality in only the affected space. Consequently, the time required to restore functionality to a building depends strongly on which components are damaged and the degree to which they are damaged.

However, as several researchers have noted, downtime is more than the time needed to make repairs or restore external utilities. Comerio [12] identifies both rational and irrational components of downtime. Rational components include the time required to repair damage and refinish spaces within the building, while irrational components include the time needed to mobilize resources and make decisions (e.g., inspect and assess the building; secure funding for repair work; commission architects and engineers to design retrofit strategies and develop construction drawings; obtain permits; hire and mobilize contractors and construction crews to complete the work). While some of these irrational components are within the control of a building owner, many are not. Furthermore, most are highly uncertain in nature, as the time required to address each component will depend on, among other things, the severity of the disaster, the strength of the regional economy, and local regulations or policies (e.g., changes to planning, zoning, or construction regulations by a local jurisdiction after an earthquake, disaster assistance provided only to specific groups of businesses or individuals, etc.). Many of these irrational components are rooted in events that take place completely outside of the built infrastructure. In other words, downtime is not simply a function of the extent and severity of building damage; it is highly dependent on aspects within the human infrastructure (e.g., availability of funding, local demand for engineering and construction services, etc.).

5. Functionality restoration curves

As the preceding discussion highlights, there are many different ways a building can lose functionality after an earthquake, most stemming from events rooted in the built infrastructure (see Fig. 1). However, the time to restore functionality to a building can be influenced strongly by events that take place within the human infrastructure. These events combine to produce a "functionality restoration curve" for a building that captures the time required to regain different levels of functionality after an earthquake (see Table 1 for definitions of each functionality level). More specifically, a functionality restoration curve tracks the recovery of a building and its supporting utilities over time to determine the resulting impact on building functionality.

Towards this end, Fig. 2 plots a functionality restoration curve for a hypothetical building. For simplicity, only two utilities, power and water, are considered. Furthermore, access to both utilities is lost after the earthquake, with power being restored before water. In the scenario depicted in Fig. 2, the building is damaged lightly and evacuated until an engineer can inspect it. During this time the building is rendered completely nonfunctional. After the inspection, the building receives a green tag (i.e., inspected placard) and can be occupied safely; however, it does not have access to power or water yet. At this point in time, the building has achieved "re-occupancy" functionality and remains at this level until power and water are restored. In this particular scenario, the building owner or manager secures a temporary supply of water, which allows the building to achieve "baseline" functionality before its normal water supply can be restored. The building owner also performs cosmetic building repairs during this time. The delay in the initiation of these repairs corresponds to the irrational components of downtime as described by Comerio [12]. In the end, the building regains "full" functionality after completing cosmetic repairs and restoring normal access to power and water.

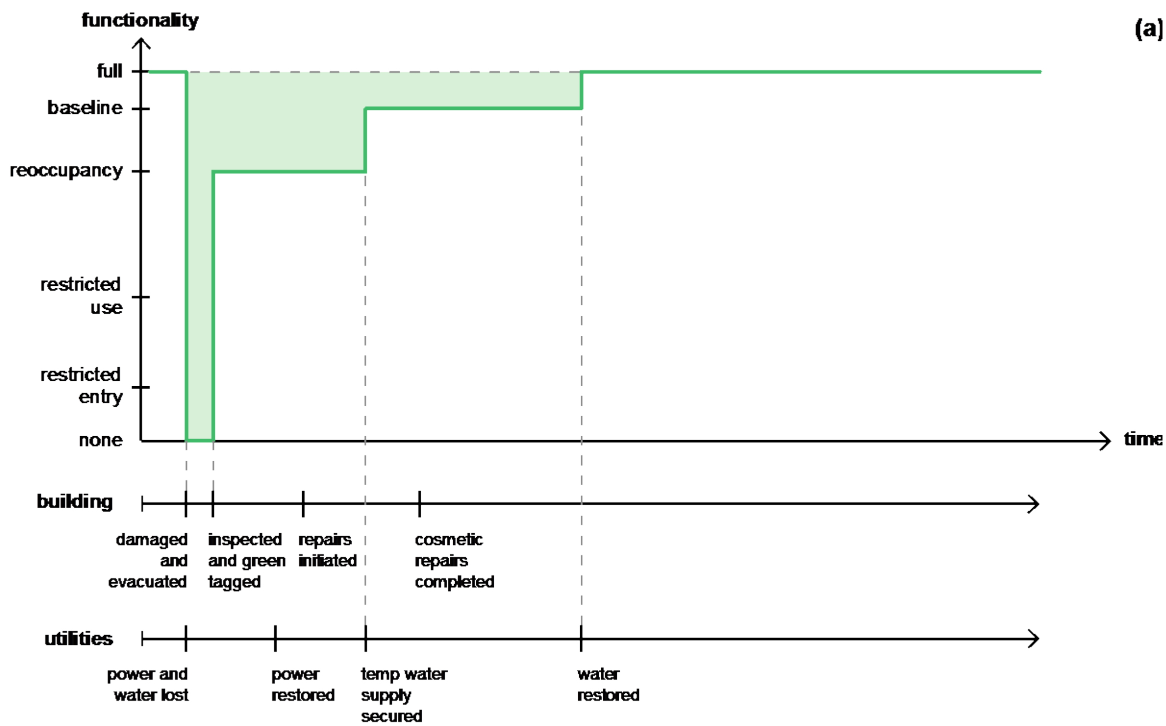

Fig. 2 – Functionality restoration curve for a building that is issued a green tag (i.e., inspected placard).

6. Functionality models

While there exists an abundance of structural analysis techniques and tools for predicting earthquake-induced forces, accelerations, and displacements in buildings, very few of them attempt to link these engineering demand parameters to the damage they cause and the subsequent loss of functionality and downtime that results.

Researchers have developed a limited number of analytical models for estimating loss of functionality in buildings after an earthquake. The following paragraphs summarize several of these efforts.

Mitrani-Reiser [13] presents a methodology for assessing building functionality via a "virtual inspector" tool that follows ATC-20 post-earthquake safety evaluation procedures [14, 15] to estimate the probability of a building receiving an unsafe placard (i.e., red tag), which would result in forcible closure and loss of functionality. In overview, a building will receive an unsafe placard if it collapses or suffers severe exterior or interior structural damage, which correspond to items in an ATC-20 assessment that would typically warrant an unsafe placard. The virtual inspector tool requires a structural model of the building to be developed and then subjected to a large number of earthquake realizations to estimate the probabilities of collapse, severe exterior damage, and severe interior damage. The probability of severe exterior damage is taken simply as the exterior structural component with the largest probability of severe damage. Similarly, the probability of severe interior damage is taken as the interior structural component with the largest probability of severe damage. These quantities are then used to compute the probability of receiving an unsafe placard. Because the methodology does not account for situations where damage to nonstructural components results in an unsafe placard, or for situations where important utilities are disrupted, the probability of receiving an unsafe placard can be considered a lower bound estimate for the probability of losing functionality. The methodology, thus, benefits from detailed structural and damage analyses.

FEMA P-58 [16] adapts the methodology outlined by Mitrani-Reiser [13] to estimate the probability of unsafe placarding after an earthquake (in addition to its more well-known procedures for estimating financial losses and downtime). In particular, FEMA P-58 refines the heuristic for translating component damage states into a building placard. It assigns an unsafe placard under either of the two following conditions: (1) "actual damage sustained by the structure is such that a life-threatening condition actually exists either through impairment of required egress or fire protection systems, or through substantive reduction in structural resistance"; or (2) "a preponderance of nonstructural damage such that there is the appearance that substantive structural damage has occurred whether or not this is actually the case" [16]. The FEMA P-58 methodology assumes that damage to most nonstructural components (with the exception of fire sprinklers and suspended ceiling systems) is unlikely to trigger an unsafe placard. Most structural components, on the other hand, have the potential to generate an unsafe placard when damaged, as the damage can reduce the gravity or lateral-load-resisting capacity of the building. For each component damage state, the methodology specifies a median fraction of damaged components from the total number of similar components at a given floor that would result in an unsafe placard. In general, this fraction decreases as the severity of the damage state increases; for example, 60% of components in damage state 2 will trigger an unsafe placard, whereas only 20% of components need to be in damage state 4 before it triggers an unsafe placard. Again, the probability of unsafe placarding computed using the FEMA P-58 methodology serves as a lower bound on the probability of losing functionality.

Porter & Ramer [17] use fault trees to compute the probability of two critical data centers losing functionality in a single earthquake in the next 50 years, an event that would disrupt the data processing capabilities of a utility provider. Towards this end, the authors develop a detailed fault tree in collaboration with facility operators to capture the various combinations of system and component failures that can impact the functionality of the facility, including failure of external lifeline systems. To estimate the probability of each critical facility losing functionality, the authors use the logic of the fault tree in conjunction with fragility functions from FEMA P-58 [16] and seismic hazard curves from the United States Geological Survey and Southern California Earthquake Center [18]. In addition to computing the probability of losing functionality, the authors outline and demonstrate a procedure for using fault trees to probabilistically estimate downtime. The procedure involves using modified fragility functions that convolve the probability of failure for a system or component with the probability it will be repaired within a certain time frame.

Jacques et al. [8] use fault trees to relate the functionality of a critical facility (specifically, hospitals) to the state of its system and components, where functionality refers to the ability to provide important clinical and support services after an earthquake. The authors identify three major factors that can impact a facility's ability to provide important services after an earthquake: staff, structure, and stuff. Staff refers to the availability of individuals (e.g., physicians, nurses, and support staff), as well as backup plans for staffing during an emergency. Structure refers to the availability of physical space (e.g., operating rooms, inpatient wards, etc.) and support infrastructure (e.g., power, water, etc.). Stuff refers to the availability of supplies (e.g., blood, oxygen, medicine, etc.) and medical equipment (e.g., MRI, sterilization machines, etc.). The authors develop separate fault trees for a wide range of clinical and support services, including surgery, intensive care, obstetrics, outpatient care, radiology, medical records, laundry, and kitchen. Each fault tree captures both partial and total disruption of a particular hospital service resulting from unavailability of staff, structure, and/or stuff. The authors derive the basic events in their trees using a combination of expert opinion and empirical data collected from reconnaissance. The fault trees are unique in that they can be used to model both loss of building functionality (via the "structures" portion of the fault tree) and organizational operability (via all three branches of the fault trees). The authors attempt to validate the predictive ability of the fault trees using data from the 2011 Christchurch earthquake. While their results are promising, the authors note that their fault trees cannot completely capture the complex emergent human behaviors, and therefore additional research is required to better understand the coupling between physical damage and human response.

7. Current design practice

In the United States, most buildings are designed in accordance with the *International Building Code* (IBC), a document that specifies minimum requirements for buildings and other engineered structures in order to safeguard the health, safety, and general welfare of the public [19]. Regarding the seismic performance of typical buildings, the primary intent of the IBC is to prevent serious injury and life loss caused by damage from earthquake ground shaking [20]. In general, the IBC achieves this intent through prescriptive design requirements that specify minimum lateral strength and stiffness for structural components and minimum anchorage, lateral bracing, and drift accommodation for nonstructural components [20]. While these design requirements have been updated and expanded significantly over the years, the primary intent of the IBC (and its predecessors) has remained essentially unchanged since 1970 [21].

The culmination of these design requirements is the performance matrix in Fig. 3, which displays seismic performance expectations for buildings designed in accordance with the provisions of the IBC. Ordinary buildings, for example, are designed to achieve collapse prevention in maximum considered earthquake ground motion, life safety in design earthquake ground motion, and immediate occupancy in frequent earthquake ground motion. Towards this end, the IBC achieves collapse prevention through provisions for structural components and life safety through provisions for nonstructural components [20]. However, the immediate occupancy performance objective, which is equivalent to the "re-occupancy" functionality level in Table 1, is not explicitly addressed within the seismic design requirements of the IBC. Consequently, the IBC lacks provisions for preventing loss of functionality in ordinary buildings after an earthquake of any intensity. This represents a major shortcoming of current design practice, and has significant impact on the post-earthquake functionality of a potentially large number of buildings in a community.

In contrast, essential facilities are expected to perform better than ordinary buildings across all levels of ground motion (see Fig. 3). To achieve this, the IBC specifies not only higher seismic design forces and smaller allowable drifts for structural components, but also additional anchorage, bracing, and testing requirements for nonstructural components. While the intention of these requirements is to maintain functionality, the effectiveness of many provisions has not been validated at higher levels of shaking [20]. Furthermore, the IBC does not require detailed analyses to explicitly verify whether a facility remains functional after an earthquake [22]. However, the provisions specified in the IBC represent a minimum set of design requirements. As such, authorities with jurisdiction over certain types of essential facilities (e.g., the Office of Statewide Health Planning and Development, which oversees hospitals in California) can, and often do, impose additional design requirements beyond what is specified in the IBC.

In an effort to move the engineering profession beyond the minimum provisions of the IBC, several organizations have developed next-generation resilience standards that, in addition to ensuring the safety of building occupants, more explicitly aim to reduce repair costs and downtime caused by earthquakes. In 2006, a subcommittee of the Existing Buildings Committee of the Structural Engineers Association of Northern California (SEAONC) began development of a seismic performance rating system for buildings. The rating system measures performance across three dimensions (safety, repair cost, and time to regain function), evaluating each on a scale from one to five stars. The subcommittee intended the rating system to be applicable to all building types and occupancies, both existing and new. In addition, they designed the rating system to serve as a common language for translating the output of different performance evaluation methodologies to a consistent performance rating. In other words, the rating system does not contain new evaluation criteria; instead it "specifies a procedure by which the outputs from existing evaluation standards (e.g., ASCE 31, FEMA P58) can be mapped to a rating value" [23]. However, the rating system does not account for either the performance of building contents or the impact of externalities (e.g., loss of power supply from the grid) on a building's overall performance. In 2011, several members of the SEAONC subcommittee formed the U.S. Resiliency Council, a nonprofit organization whose mission centers on implementing and administering the rating system.

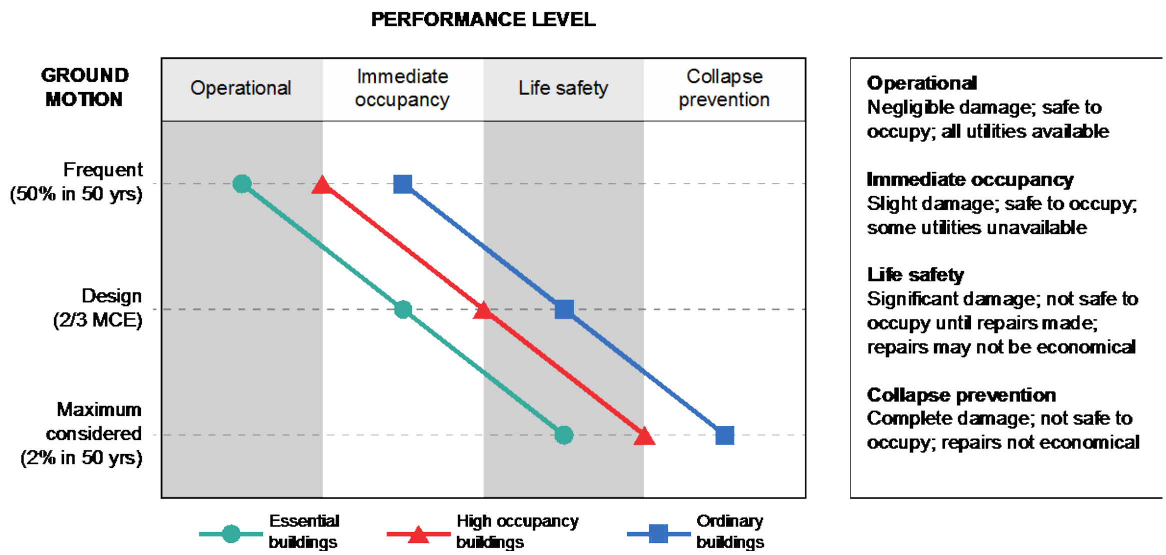

Fig. 3 – Implicit seismic performance levels for three different building categories (adapted from [20]).

Unlike the SEAONC rating system, the Resilience-based Earthquake Design Initiative (REDi) is both a seismic performance rating system and a performance assessment methodology for design and construction of new buildings. Developed by Arup, a private engineering firm, REDi is modeled after LEED, a green building certification program developed by the U.S. Green Building Council. As such, the REDi rating system comprises the same three performance tiers as LEED (platinum, gold, and silver), with each tier comprising a distinct set of resilience objectives for downtime, direct financial loss, and occupant safety. The REDi performance assessment methodology combines prescriptive design and planning requirements with a probabilistic engineering evaluation to demonstrate compliance with resilience objectives. The prescriptive requirements focus on three categories of resilience (building, organizational, and ambient), and are either mandatory or optional depending on the desired rating (e.g., platinum, gold, silver). The probabilistic engineering evaluation involves performing a modified FEMA P-58 analysis to evaluate expected losses and downtime in design earthquake ground motion (i.e., 10% probability of exceedance in 50 years). While the modified downtime methodology accounts for utility disruption and delays due to inspection, financing, engineering and contractor mobilization, and permitting, it does not account for the impact of "uncontrollable" externalities, which include hazards from adjacent buildings, restricted site access, and availability of employees to return to work [22].

8. Areas of future research

In order for the engineering profession to more effectively design buildings to regain functionality soon after a major earthquake, several important knowledge gaps and areas of future research need to be addressed. The first involves collecting better data after earthquakes. While there exists an abundance of research cataloging physical damage to various building components and systems caused by earthquakes, very few studies link this damage to its impact on functionality and downtime. Instead, most reconnaissance studies tend to focus on catastrophic failures for the purposes of updating building code provisions and best practices, which currently center on protecting life safety. While this is an important task, longitudinal studies are required to better understand how damage to particular components and systems impacts building functionality and downtime in the weeks, months, and years following an earthquake.

At present, only a small number of studies report this type of data (see, for example, [12], [7], and [8]). To facilitate additional studies of this nature, standardized data collection platforms and protocols need to be developed. Standardized data collection platforms would seek to not only capture the extent and severity of damage to important structural and nonstructural components, but also track overall recovery of the building over time, including the restoration of utilities and changes to building placarding. This data could be gathered using a mix of tools, including field surveys, aerial photography, and remote sensing technologies like light detection and ranging (LIDAR). Standardized data protocols, on the other hand, would focus on developing strategies for documenting both failures and successes, and also seek to improve the accessibility of data for the purposes of real-time recovery monitoring and long-term research. Another important component in the effort to improve data collection after earthquakes involves instrumenting more buildings to record how they respond to earthquake shaking. In particular, these instruments would allow engineers to better correlate engineering demand parameters (e.g., displacements and accelerations) with the damage recorded in field surveys. Ultimately, the data gathered using these new platforms and protocols will prove invaluable to many other research needs, as described in the following paragraphs.

Another important area of future research involves refining and validating analytical models for predicting loss of functionality and downtime. Due to the complexities involved, most current models address only a subset of the events that can impact building functionality and downtime. These models need to be expanded to include, among other things, the impact of external lifeline failure, interactions among building components and systems, “irrational” components of downtime (see [12]), and the human infrastructure. Improved empirical data is essential in this effort, as it will provide clarity regarding the influence of different events and factors on building functionality and downtime, and also help validate the accuracy and reliability of different models. For example, data from interviews of different stakeholder groups (e.g., office managers, hospital administrators, business owners, etc.) could help inform the set of building components, external utilities, and human factors that are included in a particular model. In addition, data from detailed case studies of real buildings in actual earthquakes could help illuminate the impact of different factors on recovering building functionality. In the end, these updated models would be capable of generating functionality restoration curves like the ones plotted in Fig. 2.

In addition to improving functionality models for individual buildings, new models for assessing multi-scale earthquake impacts need to be developed. In overview, these models would aim to predict the impact of damage to the built infrastructure on the availability of important community services like housing, sanitation, healthcare, education, and public transit. At the center of a multi-scale model is a critical infrastructure-based societal system (CIbSS), which is a network of buildings and lifeline systems that supports a particular community service. For example, the healthcare CIbSS includes hospitals, clinics, administrative offices, storage facilities, and the lifeline systems that support these buildings. Ideally, a multi-scale model would be able to capture the evolving topology of a CIbSS impacted by an earthquake, including the initial loss of individual components (i.e., buildings) due to damage, the propagation of damage across components, the recovery through repair efforts or adaptations taken to circumvent damaged subsystems, and the emergent links in the infrastructure system that are created and/or modified by human intervention and policy changes. Again, empirical data will prove invaluable throughout the model development and validation processes. In the end, these multi-scale models will provide new insight into the complex nature of CIbSSs and their interdependencies and also a deeper understanding of individual communities’ vulnerabilities to future earthquakes.

Ultimately, the findings from these research areas can be used to inform changes to building codes and engineering standards that aim to expand the focus of these documents from protecting life safety to minimizing downtime. When properly enforced, building codes have proven effective at reducing casualties following several recent major earthquakes; if specific provisions were developed to minimize earthquake-induced structural and nonstructural damage, they could prove similarly effective at preventing loss of functionality and minimizing downtime in buildings. New engineering tools and frameworks, such as the one proposed by Mieler et al. [24], that more comprehensively integrate the impact of structural and nonstructural damage on both life safety and building functionality could provide risk-consistent foundations for this next generation of codes and standards. As before, empirical data will play an important role in both developing new code provisions and evaluating their effectiveness once they are in place. These new provisions could be piloted in individual communities before being adopted on a wider scale. Similar changes could be made to the codes and standards that govern the performance of lifeline systems. Together, these changes would significantly enhance the resilience of the built infrastructure and help mitigate the propagation of multi-scale impacts after an earthquake.

9. Conclusions

The next frontier in earthquake engineering involves designing buildings to maintain or quickly regain functionality after a major earthquake. In support of this important effort, this paper presents the following findings:

- Loss of functionality in buildings after an earthquake can give rise to multi-scale impacts that cascade through a community across space and time, potentially disrupting important services like housing, healthcare, and education.
- A diverse set of events and factors can affect building functionality, including damage to structural and nonstructural components and systems, disruption of external utilities, and risk from nearby structures (see Fig. 1).
- Functionality restoration curves provide a compelling framework for integrating the myriad events that can cause of loss of functionality and impact its duration (see Fig. 2).
- While a wide range of tools and techniques exist for assessing loss of functionality in buildings, most require additional refinement and validation before they can be implemented in practice.
- Current design practice centers on satisfying the provisions and requirements contained in building codes and engineering standards, which have not and currently do not attempt to limit the patterns of damage in buildings that can lead to loss of functionality and downtime after a major earthquake.

In light of these findings, the paper identifies several important areas of future research, including development of improved data collection platforms and protocols, new models for assessing multi-scale earthquake impacts, and new code provisions that seek to prevent structural and nonstructural damage. These efforts will lead to significant improvements not only in the seismic performance of individual buildings but also in the overall resilience of communities. However, these efforts address a only small component of a community’s highly interactive network of infrastructures; therefore, they need to be pursued in parallel with additional efforts that seek to improve the resilience of other community components, including lifeline systems, businesses and organizations, and natural ecosystems.

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