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USING FAILURE ANALYSIS TOOLS TO ESTABLISH SEISMIC RESILIENCE OBJECTIVES FOR BUILDING COMPONENTS AND SYSTEMS

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ABSTRACT

While modern building codes have proven effective at reducing casualties caused by structural collapse following several recent earthquakes, they have been less effective at preventing damage that can lead to loss of functionality, especially in ordinary buildings (e.g., offices, factories, hotels, etc.). Because the performance of these buildings can significantly impact community recovery and resilience, it is imperative that building codes expand their current focus on protecting life safety in rare earthquakes to include provisions and requirements that aim to prevent damage and minimize loss of functionality in more frequent events. Towards this end, this paper presents a conceptual framework that directly connects performance targets for structural and nonstructural components to global resilience objectives for an entire building. The framework uses fault trees, a common failure analysis tool, to: (1) model how damage to or failure of different components and systems within a building can affect overall building functionality, and (2) provide the quantitative underpinnings for deriving consistent performance targets for building components and systems. The paper then presents a demonstration of the proposed framework to study loss of functionality in a generic commercial building and derive a set of consistent performance targets for its structural and nonstructural components. Lastly, the paper discusses potential applications of the proposed framework, including providing risk-consistent foundations for future generations of building codes and engineering standards.

INTRODUCTION

Recently, the city of Christchurch, New Zealand was impacted by a sequence of devastating earthquakes. The main shock in the sequence occurred on 4 September 2010 and was followed by several powerful aftershocks, including a major aftershock on 22 February 2011. The February event was particularly devastating, claiming the lives of 185 people and causing widespread damage to buildings and lifelines throughout the city and region. Christchurch's central business district (CBD) was hit especially hard. Nearly 90 percent of the 2,036 buildings in the CBD, most of them commercial facilities, received either a red or yellow tag [1], significantly impairing their functionality. This extensive concentration of damage resulted in large portions of the CBD being cordoned after the earthquake, with access to some areas being restricted for over two years [2]. As a result, the cordon zone impacted the functionality of buildings that were otherwise undamaged (i.e., green-tagged). It also created unprecedented challenges for the city and its businesses. Prior to the earthquake, the CBD was home to approximately 6,000 businesses and institutions that employed 25% of the city's workforce [3]. The inability of these businesses and institutions to use or even access their buildings after the earthquake was a major impediment to both the restoration of their business operations and the overall recovery of the city.

Therefore, an essential component in the effort to enhance the resilience of communities following earthquakes includes the designing of resilient buildings and infrastructure. The term resilience has been interpreted in many ways; in the context of this paper it is defined as the ability of a building to: (1) protect life safety and avoid major structural and nonstructural failures, and (2) recover functionality within an acceptable amount of time after an earthquake. Historically, building codes and engineering standards have focused primarily on achieving life-safety performance in ordinary buildings (e.g., offices, hotels, factories, etc.) when subject to rare earthquake shaking (i.e., 500-year return period). However, they have largely failed to address the need to maintain functionality in more frequent shaking (e.g., 72- or 100-year return periods), though in New Zealand ordinary buildings are expected to remain functional without any damage during very frequent seismic events (i.e., 25-year return period). In contrast, facilities with essential post-earthquake operations, i.e., hospitals, emergency response centres and police and fire stations, are typically designed to remain functional in rare ground shaking. As the experience in Christchurch highlights, ordinary buildings often have equally important roles to play after an earthquake, especially during recovery. As such, the seismic performance of these "ordinary" buildings is the focus of this paper.

An important shortcoming in modern building codes is the lack of an explicit design point for assessing loss of functionality in ordinary buildings. A "loss-of-functionality" design point is an essential component in improving the seismic resilience of buildings. However, preventing loss of functionality in a building involves a more complex set of challenges than protecting life safety. Building functionality can be affected by damage to and failure of a wide range of individual components and systems (both structural and nonstructural) within a building. In addition, interactions and interdependencies among components and systems can exacerbate the impact of seismic damage on building functionality and subsequent downtime. Furthermore, events

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external to a building can also impact its functionality (e.g., damage to an adjacent structure, being located within a cordon zone, disruption of external power and water supplies, etc.). Hence it is imperative to understand not only how failure of individual components and systems can impact functionality, but also how combinations of failures and interactions among components, systems, and the surrounding environment can affect functionality.

Towards this end, this paper proposes a conceptual framework for deriving a set of risk-consistent performance targets for building components and systems, both structural and nonstructural, from a global resilience target for the building (e.g., 10% probability of losing functionality in ground shaking with a particular return period). In overview, the framework uses fault trees to: (1) model how damage to or failure of different combinations of components and systems within a building can affect overall building functionality and (2) provide the quantitative underpinnings for deriving consistent performance targets for building components and systems. While fault trees have been used extensively in failure analyses of engineered systems, this paper proposes a novel application for the purposes of establishing consistent performance targets for design. The paper begins with an overview of the current regulatory framework (e.g., building codes and engineering standards) for designing buildings to withstand the effects of earthquake ground shaking in both the United States and New Zealand, identifying important gaps with respect to maintaining functionality in ordinary buildings. Next, it briefly examines the implications of the current regulatory framework in terms of the observed performance of nonstructural components in previous earthquakes. The paper then presents and describes the proposed conceptual framework, including a simple parametric example to help illustrate the framework and also a more realistic demonstration to study loss of functionality in a generic commercial building. Lastly, the paper discusses potential applications of the framework and areas of future research, including providing risk-consistent foundations for the next generation of building codes and engineering standards, where the aim of these documents would be to expand from protecting life safety in ordinary buildings during rare earthquakes to minimizing loss of functionality following more frequent ones.

CURRENT REGULATORY FRAMEWORK FOR SEISMIC DESIGN OF BUILDINGS

To mitigate the impact of earthquakes, many communities in seismically active regions have enacted regulatory frameworks to ensure minimum levels of performance for buildings. In general, a regulatory framework provides the legal and technical basis for allowing an engineered system to operate through all phases of its lifecycle. The following discussion focuses on a small but important piece of this regulatory framework: the building codes and engineering standards in the United States and New Zealand that establish seismic performance expectations, either implicit or explicit, for buildings. When properly enforced, these documents have proven effective at reducing the number of casualties caused by structural collapse and falling debris from buildings during earthquake ground shaking. However, they have been less effective at preventing physical damage that can impact building functionality and cause significant downtime and economic loss. Scawthorn (2003) and others [4] document a steady increase in economic losses following earthquakes over the past two decades. In fact, some of the most costly and disruptive earthquakes have taken place in countries with modern building codes that are well enforced, including Chile, Japan, and New Zealand.

The effectiveness of modern building codes at reducing casualties can be attributed primarily to the intent of these documents. Historically, seismic design provisions for ordinary buildings have centred on protecting life safety in a major earthquake. Consequently, seismic provisions for structural components have been given much more attention than those for nonstructural components [5, 6]. Typically, nonstructural components are grouped into the following three categories: (1) architectural finishes, (2) mechanical, electrical and other building services, and (3) building contents. While structural components play a vital role in the overall seismic response of the building, nonstructural components often play a critical part in maintaining functionality. Furthermore, because nonstructural components account for approximately 75-90% of a building's initial construction cost [7], they are often a primary source of economic loss after an earthquake [6].

United States

At the heart of the current regulatory framework for the seismic design of buildings in the United States is the *International Building Code* (IBC), a document that specifies minimum requirements for buildings and other structures in order to safeguard the health, safety and general welfare of the public [8]. With respect to the seismic performance of ordinary buildings, the primary intent of the IBC is to "prevent serious injury and life loss caused by damage from earthquake ground shaking" [9]. Subsequently, a major thrust of the IBC is to prevent structural collapse in very rare ground motion, referred to as the maximum considered earthquake (MCE) ground motion, which has a 2,500-year return period. A secondary thrust of the IBC is that "life threatening damage, primarily from failure of nonstructural elements in and on structures, will be unlikely in an unusual but less rare earthquake ground motion, which is given as the design earthquake ground motion (defined as two-thirds of the MCE)" [9]. The IBC achieves its primary intent through prescriptive design requirements that specify minimum lateral strength and stiffness for structural systems and minimum anchorage, lateral bracing and drift accommodation for nonstructural components. Many of the current design requirements for nonstructural components can be found in Chapter 13 of ASCE 7 [10], though additional requirements are scattered throughout a wide range of other codes and standards, as documented in FEMA (2012) [6].

The culmination of these design requirements is the performance matrix shown in Figure 1, which displays seismic performance expectations for buildings designed in accordance with the provisions of the IBC. Ordinary buildings, for example, are designed for *collapse prevention* in the MCE ground motion, *life safety* in the 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. However, the third performance objective, immediate occupancy in frequent ground motion, is not explicitly addressed in the IBC's seismic design requirements. This represents a major shortcoming of the current regulatory framework in the United States, and has significant impact on the resilience of ordinary buildings and ultimately the communities in which they reside.

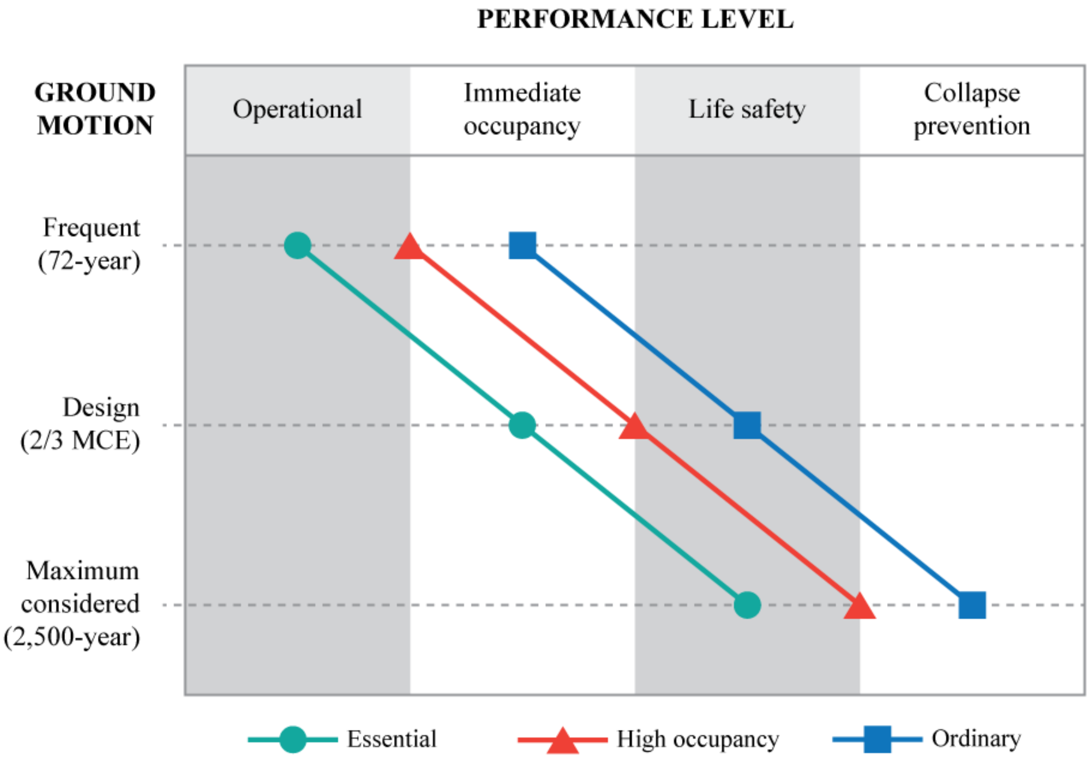


Figure 1: Seismic performance objectives for different building occupancies specified in the NEHRP Recommended Provisions (adapted from BSSC 2003 [11] and BSSC 2009 [9]).

New Zealand

The New Zealand Building Code (NZBC) adopts a performance-based approach that establishes functional and performance requirements for buildings, specifying expected performance outcomes rather than prescribing specific solutions. Currently, the building code specifies two performance criteria for achieving tolerable levels of safety and the health of building occupants: (1) the ultimate limit state (ULS) prescribes *life safety* under rare seismic events (i.e., 500-year return period) and (2) the serviceability limit state (SLS) prescribes *serviceability* under very frequent seismic events (i.e., 25-year return period). Despite lacking an explicit design point for collapse prevention, the NZBC provides a high degree of confidence against collapse implicitly through structural redundancy requirements. In the aftermath of the Christchurch earthquake in 2011, the NZBC is undergoing a revision with the objective of providing more transparency around the existing criteria and not necessarily improving the goal of achieving functionality in ordinary buildings at other seismic intensities.

The earthquake loading Standard of New Zealand, NZS 1170.5:2004, specifies design requirements for nonstructural components in Section 8 [12]. To comply with the NZBC, these design requirements aim to protect life safety by avoiding falling hazards or any other dangerous consequences at the ULS. Currently, efforts are underway to revise NZS 1170.5 to identify and include an intermediate checkpoint between the ULS and SLS that aims to prevent loss of functionality caused by nonstructural damage. Exclusive design Standards are available for individual nonstructural components, including NZS 2785:2000 for suspended ceilings [13], NZS 4541:2013 for automatic fire sprinkler systems [14] and NZS 4219:2009 for building services [15]. However, a lack of coordination and consistency amongst the design requirements in these Standards is apparent, as nonstructural systems have performed poorly in several recent earthquakes in New Zealand.

OBSERVED PERFORMANCE OF NONSTRUCTURAL COMPONENTS IN PAST EARTHQUAKES

FEMA (2012) [6] identifies three primary types of risk associated with earthquake-induced damage to nonstructural components: (1) life safety, (2) property loss and (3) functional loss. There exists a growing body of literature documenting the impact of nonstructural damage on these three risk categories in past earthquakes. Several observations can be made from these studies. First, a significant disparity exists between the threshold for nonstructural damage and structural damage. This observation is supported by evidence from several recent earthquakes of buildings suffering extensive nonstructural damage while experiencing only minor structural damage [16, 17, 7, 18]. This disparity exists, in part, due to a historical lack of coordination among the code committees charged with developing design requirements for various nonstructural components and systems, resulting in an uneven patchwork of provisions. In addition, the seismic design of nonstructural components and systems typically involves a wide range of professions, including structural engineers, architects, mechanical engineers and electrical engineers. A lack of coordination among these groups often results in nonstructural components that are not as robust as structural components [19]. Furthermore, the provisions of most modern building codes have been formulated with the expectation that nonstructural damage occurs at a lower level of ground motion than structural damage in ordinary buildings.

Secondly, following many recent earthquakes, losses from nonstructural damage to buildings frequently exceed those from structural damage [16, 6]. In a study of office, hotel, and hospital buildings, Miranda and Taghavi (2003) [7] found that nonstructural components account for approximately 82%, 87% and 92% of the total monetary investment in each building category, respectively. Furthermore, due to the historical intent and focus of modern building codes, nonstructural components are more vulnerable to damage and failure in earthquakes than structural components. Taken together, this higher monetary value and increased vulnerability helps explain why losses for nonstructural components often exceed those for structural components.

Thirdly, nonstructural damage can have profound impact on building functionality. Most significantly, nonstructural damage has been a major reason for hospital evacuations following several earthquakes, including the 1994 Northridge earthquake [19, 20, 6] and the 2010 Chile earthquake [17, 18]. Collapse of ceiling systems and cracking of interior partitions can give rise to unsanitary conditions in hospitals that lead to evacuation of impacted areas. In addition, failure of water pipes can cause significant secondary damage to building contents and architectural finishes, again leading to the evacuation of individuals in the affected areas. Nonstructural damage in ordinary buildings can have similarly disruptive impacts [19, 6, 17].

Fourthly, most post-earthquake reconnaissance studies provide evidence of nonstructural damage that is largely anecdotal in nature. In other words, researchers tend to observe only damaged buildings, thus providing an incomplete picture of overall performance after an earthquake. Often the shear physical size of the impacted area precludes a systematic and comprehensive survey of buildings, which makes it difficult to, for example, determine which types of ceilings, sprinkler systems, or storage racks perform best [19]. Consequently, this lack of data makes it challenging to validate the effectiveness of seismic design requirements for nonstructural components. Several researchers have proposed nonstructural damage databases [21, 22], however these efforts appear to have been abandoned, as FEMA (2012) [6] recommends "development of a standardized framework for the collection of future nonstructural earthquake damage data."

CONCEPTUAL FRAMEWORK

FEMA (2012) [6] observes, "As the earthquake engineering community moves toward more comprehensive earthquake standards and expectations of improved seismic performance, and as the public demands a higher level of earthquake protection, it is important to understand the significance of nonstructural damage." As the preceding discussion highlights, nonstructural components play vital roles in not only protecting life safety but also maintaining building functionality and mitigating economic losses. However, in the current regulatory framework, nonstructural components are given less attention than structural components and are governed by a patchwork of provisions and requirements that have been developed in an uncoordinated fashion. The preceding discussion also makes it clear that the issues involved in preventing loss of functionality are markedly different than those associated with protecting life safety. Hence, there is a need for a new set of design requirements that address in a more comprehensive fashion the impact of structural and nonstructural damage on both life safety and building functionality. The following sections describe one such design framework. In overview, the proposed framework uses fault trees to: (1) model how damage to or failure of different structural and nonstructural components and systems affects overall building functionality, and (2) provide the quantitative underpinnings for deriving consistent performance targets for these building components and systems.

Fault trees

At the core of the proposed conceptual framework are fault trees. 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 [23]. They have been used to study a wide variety of engineered systems, ranging from nuclear power reactors and space shuttles to hospitals and electrical power grids. Figure 2 provides a simple example of a fault tree for a hypothetical fire suppression system in a building to illustrate basic concepts. The topmost box in Figure 2 is referred to as the top event in the tree and, in this example, represents failure of the entire fire suppression system (i.e., the undesired state for the system). Directly beneath the top event is an OR-gate. To pass through an OR-gate, one or more of the events directly beneath it must occur. In this example, there are two connected events: "sprinkler system damaged" and "water supply unavailable." Consequently, the fire suppression system will fail if either the sprinkler system is damaged or the water supply is unavailable. Directly beneath the "water supply unavailable" intermediate event is an AND-gate. To pass through an AND-gate, all events directly beneath it must occur. In this example, there are two connected events: "external utility lost" and "backup supply fails." Both of these events must occur for the water supply to be unavailable.

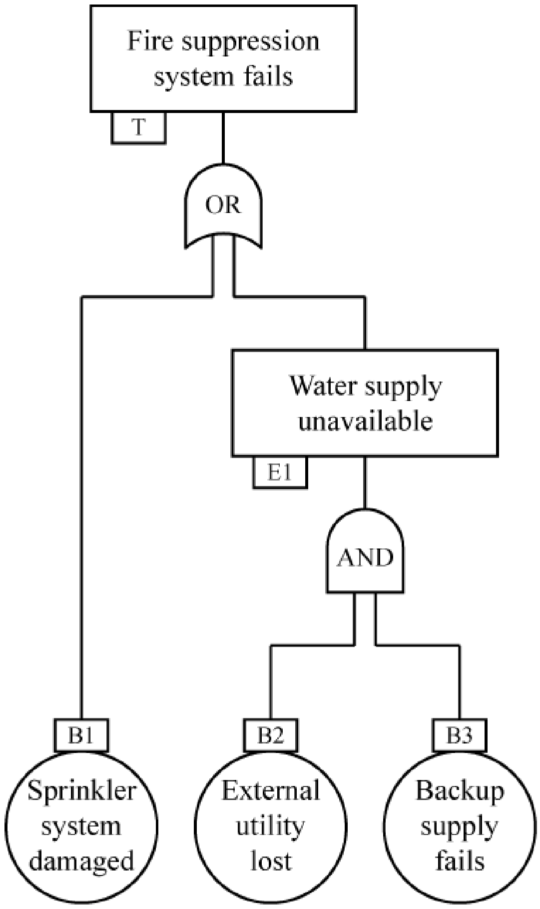


Figure 2: Example of a simple fault tree that captures failure of a hypothetical fire suppression system in a building.

Circles in the fault tree are referred to as basic events, which are events whose probability of occurrence can be estimated directly using empirical or predictive data [24]. Basic events are often tied to a particular damage state or failure mode of an individual engineered system or component. Rectangles below the top event are referred to as intermediate events, which are events whose probability cannot be estimated directly. Instead, they must be computed using the logic of the tree and the probabilities of basic events (i.e., a bottom-up analysis). Towards this end, the fault tree in Figure 2 can be represented using the following Boolean expression:

$$T = B1 \cup E1 = B1 \cup (B2 \cap B3) \quad (1)$$

The symbols ∪ and ∩ in Equation 1 represent the Boolean logic operator for an OR-gate and AND-gate, respectively. The Boolean expression in Equation 1 can be used to compute the probability of the top event of the fault tree, P(T), as follows:

$$P(T) = P[B1 \cup (B2 \cap B3)] = P(B1) + P(B2 \cap B3) - P(B1 \cap B2 \cap B3) \quad (2)$$

If basic events B1, B2, and B3 are assumed to be independent (i.e., the occurrence of B1 does not affect the probability of occurrence of either B2 or B3, and vice versa), Equation 2 simplifies to the following:

$$P(T) = P(B1) + P(B2) \times P(B3) - P(B1) \times P(B2) \times P(B3) \quad (3)$$

where P(B1) is the probability of the sprinkler system being damaged, P(B2) is the probability of losing the external utility supply and P(B3) is the probability of failure for the backup utility supply. Each of these probabilities can be estimated directly from empirical or predictive data.

Methodology

As Figure 2 demonstrates, fault trees offer a compelling framework for qualitatively capturing the myriad combinations of events that can affect building functionality or, alternatively, life safety. They can also provide the quantitative underpinnings for deriving a set of consistent performance targets for building components and systems, both structural and nonstructural. The flowchart in Figure 3 describes a novel methodology for computing risk-consistent performance targets using the structure of a fault tree. The following paragraphs describe the methodology in more detail.

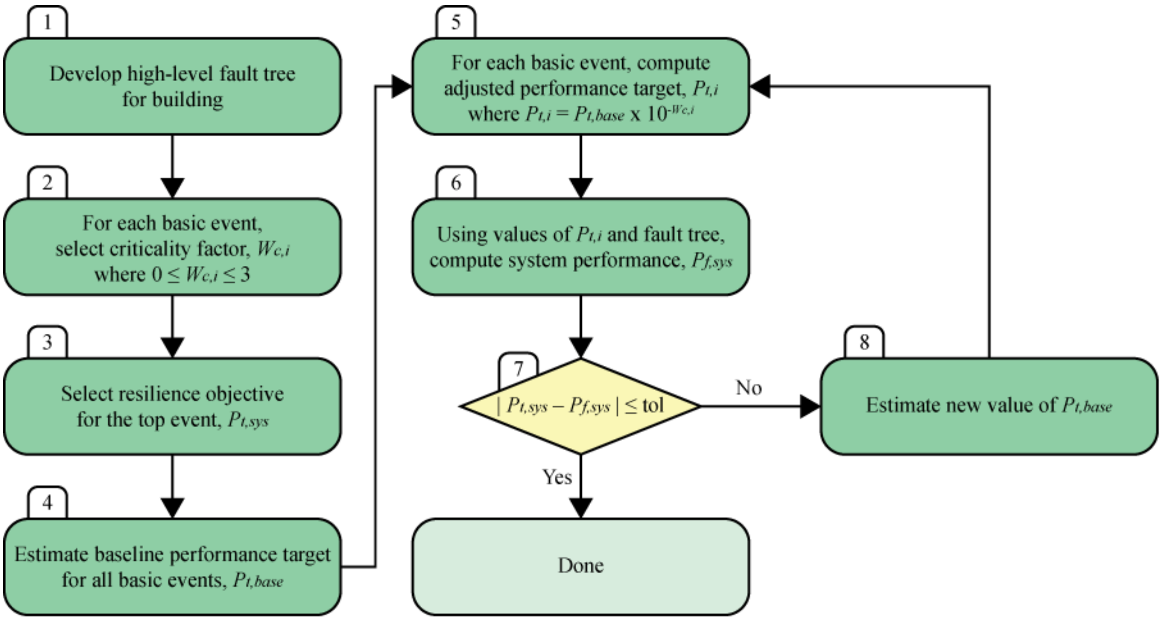


Figure 3: Methodology for computing risk-consistent performance targets for basic events from a global resilience objective for the top event in a fault tree.

In overview, the methodology employs an iterative algorithm to compute performance targets for each basic event, $P_{t,i}$, from a resilience objective for the top event, $P_{t,sys}$. This computation represents a novel application, as it involves inverting the typical bottom-up fault tree analysis procedure. In other words, the methodology starts at the top of the fault tree with a resilience objective for the top event, which in the case of buildings can be selected by the building owner, code development committee, or other stakeholder groups. It then uses the structure of the fault tree to derive risk-consistent performance targets for events below. However, in inverting the traditional bottom-up process, there exists an infinite set of basic event probabilities that could satisfy the resilience objective for the top event. In order to simplify the problem, the methodology utilizes an iterative algorithm that initially constrains the probabilities of each basic event to be equal. Then, to provide additional flexibility, the methodology makes use of a relative weighting scheme that enables different performance targets to be computed for different basic events based on the event's importance. As such, the specified resilience objective for the top event is "distributed" among the basic events in proportion to the consequences of each event on overall building performance.

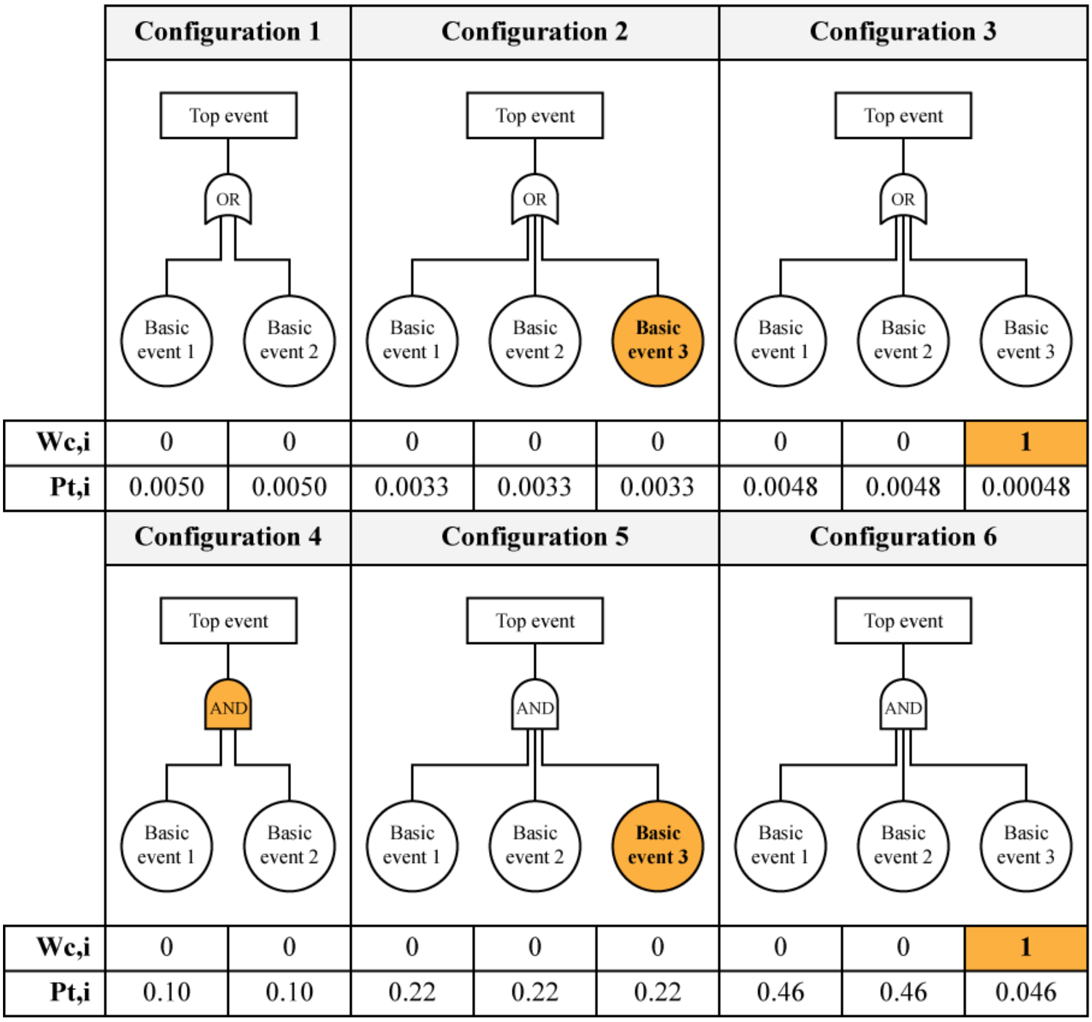
The first step in Figure 3 involves developing a fault tree for the system under consideration (e.g., a building) and the undesired state that is to be avoided (e.g., loss of functionality, threat to life safety). This step is one of the most critical; failure to adequately identify all possible combinations of events that can cause the chosen undesired state for the system will result in an incomplete set of performance targets.

The second step in Figure 3 involves selecting a criticality factor, $W_{c,i}$, for each basic event in the fault tree, where the criticality factor measures the relative impact a particular event has on overall system performance. As such, criticality factors serve as a relative weighting scheme in the iterative algorithm for computing performance targets. Within the proposed framework, the criticality factor must be a number between zero and three. A value of zero indicates the event is of normal importance, while a value of three indicates it has highest importance. A criticality factor of one will result in a performance target for an event that is ten times ($=10^1$) smaller than the performance target for an event with a criticality factor of zero. Similarly, a criticality factor of two will result in a performance target for an event that is one hundred times ($=10^2$) smaller than the performance target for an event with a criticality factor of zero. As a result of this relationship, it is recommended that $W_{c,i}$ not exceed a value of three in order to avoid excessively small values for performance targets. Criticality factors can be selected using expert opinion, empirical data from past earthquakes, or results from previous vulnerability analyses. Later sections of this paper provide an example that demonstrates how criticality factors can be chosen for a commercial building using a combination of expert opinion and guidance from various engineering standards.

The third step in Figure 3 involves selecting a resilience objective for the top event, $P_{t,sys}$. This resilience objective is equivalent to the desired probability of failure for the system under consideration (e.g., 10% probability of losing functionality in ground shaking with a particular return period). Once both the criticality factors, $W_{c,i}$, and the resilience objective, $P_{t,sys}$, have been specified, an iterative algorithm is utilized to compute performance targets for each basic event, $P_{t,i}$. The algorithm employs the following procedure. Firstly, estimate an initial baseline performance target for all basic events, $P_{t,base}$ (e.g., $P_{t,base} = 0.001$) (see Step 4 in Figure 3). Secondly, for each basic event, compute the adjusted baseline performance target, $P_{t,i}$, where $P_{t,i} = P_{t,base} \times 10^{-W_{c,i}}$ (see Step 5). Thirdly, use these adjusted performance targets and the structure of the fault tree to compute the actual probability of the top event, $P_{f,sys}$ assuming independence of events (see Step 6). Fourthly, check if the actual probability of the top event, $P_{f,sys}$, is within the specified tolerance of the resilience objective, $P_{t,sys}$ (see Step 7). If not, then adjust the baseline performance target for all basic events, $P_{t,base}$, and repeat the process from Step 5 (see Step 8). If, on the other hand, $P_{f,sys}$ and $P_{t,sys}$ are within the specified tolerance, the process is complete. The resulting set of performance targets, $P_{t,i}$, is essentially the maximum allowable probability of failure for each basic event that satisfies the resilience objective for the system, $P_{t,sys}$.

Parametric study

To demonstrate the implications of the methodology depicted in Figure 3, a simple parametric study is provided. It examines six different fault tree configurations to evaluate the impact of three parameters (gate type, number of basic events and criticality factor) on the performance targets computed for each basic event. Figure 4 shows each of the six configurations and the resulting performance targets computed for each basic event. For all six configurations, the selected resilience objective for the top event, $P_{t,sys}$, is 1% probability of failure in ground shaking with a particular return period. Configurations 1 and 4 comprise a top event with two basic events beneath; configurations 2, 3, 5, and 6 comprise a top event with three basic events beneath. Configurations 1, 2 and 3 feature an OR-gate; configurations 4, 5 and 6 feature an AND-gate. The criticality factor $W_{c,i}$ for all basic events is 0 except for configuration 3 and 6, where the criticality factor for one of the three basic events is set to 1.



	Configuration 1		Configuration 2			Configuration 3		
	Basic event 1	Basic event 2	Basic event 1	Basic event 2	Basic event 3	Basic event 1	Basic event 2	Basic event 3
Wc,i	0	0	0	0	0	0	0	**1**
Pt,i	0.0050	0.0050	0.0033	0.0033	0.0033	0.0048	0.0048	0.00048

	Configuration 4		Configuration 5			Configuration 6		
	Basic event 1	Basic event 2	Basic event 1	Basic event 2	Basic event 3	Basic event 1	Basic event 2	Basic event 3
Wc,i	0	0	0	0	0	0	0	**1**
Pt,i	0.10	0.10	0.22	0.22	0.22	0.46	0.46	0.046

Figure 4: Performance objectives for each of the six fault tree configurations included in the parametric study. The selected resilience objective for the top event, $P_{t,sys}$, for all six configurations is 1% probability of failure in ground shaking with a particular return period.

After computing the required performance targets for each configuration using the methodology outlined in the previous section, the following observations can be made. First, comparing configurations 1 and 4 reveals that gate type has a significant impact on the required performance targets for basic events, with OR-gates requiring much more stringent performance (i.e., lower probability of failure) than AND-gates. This is due to the nature of the gates themselves: only one event beneath an OR-gate needs to occur in order for the system to fail, whereas all events beneath an AND-gate need to occur in order for the system to fail. Second, comparing configurations 1 and 2 reveals that adding an additional basic event beneath an OR-gate necessitates more stringent performance (i.e., lower probability of failure) for all basic events because, in essence, an additional failure mode has been added to the system. Third, comparing configurations 4 and 5 reveals that adding an additional basic event beneath an AND-gate requires less stringent performance (i.e., higher probability of failure) for all basic events because an additional line of defence or redundancy has been added to the system. And fourth, comparing configurations 2 and 3 (and 5 and 6) reveals that increasing the criticality factor for one basic event from 0 to 1 requires less stringent performance for the remaining basic events.

DEMONSTRATION

This section presents a detailed demonstration of the proposed conceptual framework to study loss of functionality in a generic commercial building. Figure 5 shows the fault tree developed for this purpose. It captures, at a high level, the various combinations of events and failures that can lead to loss of functionality in a commercial building after an earthquake. As such, the fault tree was created without reference to a specific building design or configuration, meaning that the events contained in the tree represent high-level, generic failures that should apply to a wide range of building designs and configurations.

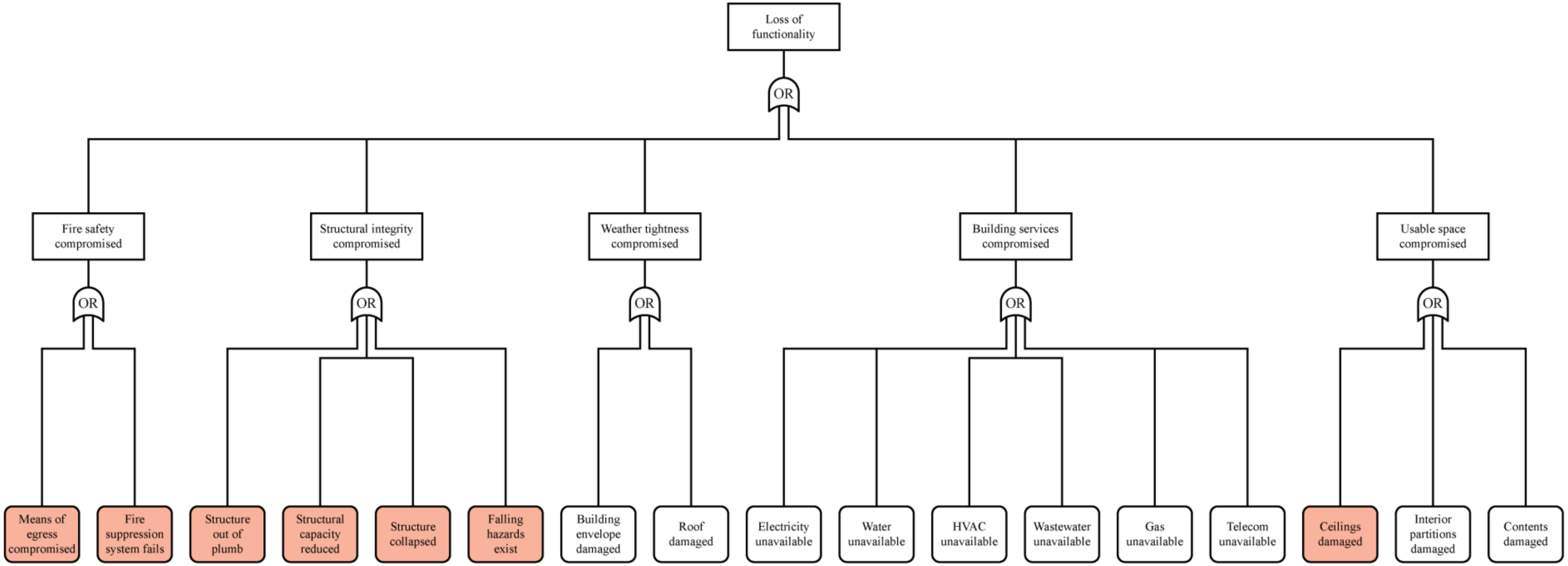
The fault tree in Figure 5 was developed using a two-pronged approach. The first part of the approach involved reviewing building component taxonomies [25, 26, 27, 28] in order to populate basic events in the fault tree (i.e., development from the bottom up). In particular, the following categories were developed to help organize components and systems within a building: structural elements (e.g., beams, columns, braces, shear walls, foundations); architectural finishes (e.g., partitions, ceilings, windows, doors, exterior cladding); building services (e.g., electrical and lighting, plumbing, sprinklers, HVAC, telecom); and contents (e.g., computers, furniture, equipment). The second part of the approach involved reviewing previous studies of both fault trees [29, 30, 31, 32] and building performance in past earthquakes [33, 34] to develop intermediate events and give structure to the tree (i.e., development from the top down). Despite the comprehensive approach, the fault tree does not capture the full set of events that can impact building functionality; for example, it does not address loss of functionality stemming from damage to an adjacent structure, instability of a nearby slope, or being located within a cordon zone. Instead, the fault tree in Figure 5 focuses on events that take place within the building envelope, as the occurrence of these events is typically within the control of the engineer or analyst.

The top event in Figure 5 represents loss of building functionality. Beneath this top event are five high-level intermediate events: fire safety compromised, structural integrity compromised, weather-tightness compromised, building services compromised, and usable space compromised. These five events are connected to the top event through an OR-gate, meaning that the occurrence of any one of these five events will result in loss of functionality for the building. Below each high-level intermediate event are various “basic” events, where the quotation marks indicate that these events are not basic events as traditionally defined (i.e., events whose probabilities of occurrence can be estimated directly using empirical or predictive data). Instead, they are events for which performance targets are to be computed. In most cases, the “basic” event corresponds to failure of or damage to a particular structural or nonstructural component in a building. Table 1 provides additional detail for each “basic” event. In Figure 5, these events are drawn as rectangles with rounded corners to indicate that, in this case, these events are intermediate events that are being treated as basic events. Each “basic” event is connected to the intermediate events above through OR-gates, indicating that the occurrence of any single “basic” event will result in the occurrence of the corresponding intermediate event.

Consequently, the structure and logic of the fault tree in Figure 5 is such that the occurrence of any of the 17 “basic” events will render the building unusable, highlighting the fact that a wide range of factors can affect building functionality after an earthquake. A closer inspection of Table 1, however, reveals that different “basic” events can have profoundly different impact on 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 “basic” events can result in a building receiving a red or yellow tag 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 Figure 5, correspond to specific items on post-earthquake safety evaluation forms that can trigger a red tag (see *ATC-20 Rapid/Detailed Evaluation Safety Assessment Forms* in the United States and *Level 1/2 Rapid Assessment Forms* in New Zealand). In contrast, other “basic” events may impact a limited portion of a building, resulting in loss of functionality in only the affected space.

Therefore, the “basic” events in Figure 5 should have different criticality factors and, ultimately, different performance targets. Towards this end, Figure 5 displays the criticality factors, $W_{c,i}$, selected for each of the 17 “basic” events in the fault tree. The values, which range from zero (“HVAC unavailable”) to three (“Structure collapsed”), were selected using expert opinion in conjunction with post-earthquake safety evaluation forms and the nonstructural seismic risk ratings contained in Appendix E of FEMA (2012) [6]. The criticality factors presented in Figure 5 were developed specifically for a generic commercial building and, therefore, should be adjusted accordingly for different building occupancies (e.g., hospitals, schools, etc.).

Figure 5 also displays the performance targets computed for each “basic” event, $P_{t,i}$, using the methodology described in the previous section. These performance targets correspond to a resilience objective of 10% probability of losing functionality in ground shaking with a particular return period (i.e., 100 years). In other words, in order for the probability of occurrence of the top event to be 10% or less, the probability of occurrence of each “basic” event cannot exceed the values shown in Figure 5.



Criticality factor, *Wc,i*	2.0	2.0	2.5	2.5	3.0	2.0	1.5	1.5	1.0	1.0	0.0	0.5	1.0	0.5	1.5	1.0	0.0
Performance target, *Pt,i*	3.3×10^{-4}	3.3×10^{-4}	1.0×10^{-4}	1.0×10^{-4}	3.3×10^{-5}	3.3×10^{-4}	1.0×10^{-3}	1.0×10^{-3}	3.3×10^{-3}	3.3×10^{-3}	3.3×10^{-2}	1.0×10^{-2}	3.3×10^{-3}	1.0×10^{-2}	1.0×10^{-3}	3.3×10^{-3}	3.3×10^{-2}

Figure 5: Fault tree for capturing loss of functionality in a generic commercial building, including criticality factors ($W_{c,i}$) and performance targets ($P_{t,i}$) for each "basic" event corresponding to a global resilience objective ($P_{t,sys}$) of 10% probability of losing functionality in ground shaking with a particular return period.

Table 1: Detailed descriptions of each "basic" event in Figure 5

"Basic" event	Description
Means of egress compromised	Horizontal or vertical means of egress blocked by toppled building contents or rendered unsafe by damage to stairs, elevators, and/or corridors. Could result in red tag and potentially affect usability of entire building.
Fire suppression system fails	Fire sprinklers and/or piping damaged, pumps fail, and/or water supply unavailable. Could result in red tag and potentially affect usability of entire building.
Structure out of plumb	Permanent structural drift (arising from damage to structural framing or from differential foundation settlement) poses a risk to either occupant comfort or safety. Applied Technology Council (2012) recommends a median residual drift ratio of 0.2% in order to avoid realignment of the structural frame after an earthquake. Will result in red tag and affect usability of entire building.
Structural capacity reduced	Damage to the building's lateral system, gravity system, or foundation reduces its ability to safely resist vertical and/or lateral loads. The exact nature of this damage depends on the structural system. Will result in red tag and affect usability of entire building.
Structure collapsed	Catastrophic failure of the building's structural system, resulting in partial or total collapse of the building. Will result in red tag and affect usability of entire building.
Falling hazards exist	Damage to chimneys, parapets, or façades weakens these elements to the point that they could fail with little or no warning (assuming the building has these elements). Will likely affect usability of part of the building, but could also result in red tag and potentially affect usability of entire building.
Building envelope damaged	Damage to exterior walls, cladding, façades, windows, or other elements affects the building's ability to prevent moisture intrusion and/or maintain a comfortable climate inside. Damage does not represent a life-safety hazard, but will likely affect usability of part of the building.
Roof damaged	Damage to roof coverings, finishes, or structural framing affects the building's ability to prevent moisture intrusion. Will likely affect usability of part of the building.
Electricity unavailable	Damage to internal electrical systems and equipment (e.g., conduits, switchgear, cabinets, etc.) or loss of supply from the grid disrupts the building's power service. Could potentially affect usability of entire building.
Water unavailable	Damage to internal water distribution systems and equipment (e.g., pipes, pumps, etc.), power failure, or loss of supply from the grid disrupts the building's water service. Could potentially affect usability of entire building.
HVAC unavailable	Damage to internal systems and equipment (e.g., ducts, boilers, chillers, etc.) or power failure disrupts the building's HVAC service. Could potentially affect usability of entire building.
Wastewater unavailable	Damage to internal wastewater systems and equipment (e.g., pipes, pumps, etc.), power or water failure, or loss of connection to the sewer disrupts the building's wastewater service. Could potentially affect usability of entire building.
Gas unavailable	Damage to internal gas distribution systems and equipment (e.g., pipes, equipment, etc.), power failure, or loss of supply from the grid disrupts the building's gas service. Could potentially affect usability of entire building.
Telecom unavailable	Damage to internal telecom systems and equipment (e.g., conduits, equipment, etc.), power failure, or loss of connection to the network disrupts the building's telecom service. Could potentially affect usability of entire building.
Ceilings damaged	Damage to ceilings (e.g., dislodged or fallen acoustic ceiling tiles, separation of plaster or gypsum ceiling from structural framing, etc.) impacts the usability of the affected space and potentially the safety of occupants. Could result in red tag and will likely impact usability of part of the building.
Interior partitions damage	Damage to interior partitions impacts the usability of the affected space and potentially the safety of occupants. Will likely impact usability of part of the building.
Contents damaged	Damage to contents (e.g., furnishings, equipment, computers, etc.) impacts the usability of the affected space and potentially the safety of occupants. Will likely impact usability of part of the building.

POTENTIAL APPLICATIONS AND AREAS OF FUTURE RESEARCH

One potential application of the proposed conceptual framework involves using it to provide risk-consistent foundations for the next generation of building codes and engineering standards, where the aim of these documents would be to expand from protecting life safety in ordinary buildings during rare earthquakes to minimizing loss of functionality and downtime in more frequent events. To do so, the performance of both structural and nonstructural components (including their interdependencies) needs to be given more thorough consideration. As the previous section demonstrated, the proposed conceptual framework can be used to establish a set of risk-consistent performance targets for structural and nonstructural components that achieves a global resilience objective for loss of functionality (see Figure 5). These performance targets could serve as risk targets for code provisions and design requirements for different building components and systems (e.g., lateral load resisting system, ceiling system, interior partitions, plumbing, etc.), and could also help improve coordination among the many different code-writing committees. For example, the committee charged with developing the seismic design standard for suspended ceiling systems would aim to achieve the target specified in Figure 5 (i.e., a 1.0×10^{-3} probability of failure in ground shaking with a particular return period) through specific strength and stiffness requirements for ceiling framing and anchorage. In addition, the performance targets in Figure 5 could provide guidance to utility operators for improving the reliability of local and regional networks.

Before such an application can be pursued, several outstanding issues need to be addressed. One issue centres on improving the algorithm for computing performance targets (see Figure 3). At present, the algorithm does not address the costs of achieving the desired levels of performance for particular building components and systems. Because the building code aims to balance cost and performance, it would be beneficial to develop an optimization algorithm that computes a set of performance targets for building components and systems that satisfies a global resilience objective while also minimizing total cost. In order to do so, linkages between cost and performance need to be investigated and defined for a wide range of structural and nonstructural components. These linkages will help ensure that performance targets computed for a particular component or system are proportional not only to its criticality in maintaining building functionality but also its impact on overall cost.

In addition, the algorithm currently does not account for correlation among basic events when computing performance targets (e.g., damage to a concrete shear wall damages attached piping and fixtures). While the assumption of independence is important for the practicality of the framework, the impact it has on the computed performance targets could be significant. In general, the interactions among building systems and components have not been well studied, especially for nonstructural components. Consequently, this issue represents an important area of future research, and could be addressed within the proposed framework using several potential strategies, including development of a dependence matrix of correlation coefficients that feeds into the iterative algorithm or, alternatively, development of a more refined fault tree that captures interactions among components via its structure. Central to all of these strategies, however, is the availability of empirical or experimental data that not only documents the myriad interactions among building components but also connects these interactions with their impact on building functionality and downtime. Unfortunately data of this nature is currently lacking.

Another outstanding issue involves validating the appropriateness of the performance targets computed by the proposed framework. The appropriateness of performance targets is a function of several key inputs to the framework. The first is the structure of the fault tree itself. As stated previously, the fault tree in Figure 5 was developed to capture, at a high level, loss of functionality in a generic commercial building. Therefore, it will likely require modification to more accurately capture loss of functionality for a specific commercial use (e.g., office, retail, hospitality, etc.) or different occupancy class (e.g., hospital, apartment, etc.). These differences can be elucidated through a combination of empirical studies of a wide range of buildings after past earthquakes and surveys of building occupants and owners to ensure that fault trees accurately capture the various combinations of events and failures that can impact building functionality.

The second key input is the global resilience objective, as it directly controls the performance of structural and nonstructural components and systems and, consequently, the resilience of the building. This paper has made repeated reference to the following generic resilience objective: 10% probability of losing functionality in ground shaking with a particular return period. If the proposed framework were to be used in code development applications, a return period needs to be selected for ground shaking. Obviously, buildings designed to remain functional in more rare ground motions (e.g., 500-year return period versus 72-year) will have enhanced resilience. Similarly, a building designed to have 1% probability of losing functionality will be more resilient than one designed for 10%, assuming the same ground shaking. Resilience objectives could be time-based instead of scenario-based; for example 1% annual probability of earthquake-induced loss of functionality, or 10% probability of losing functionality for more than a month in ground motion with 100-year return period. These time-based objectives would necessitate only slight modifications to the proposed framework, mainly in the algorithm for computing performance targets. These modifications could be guided by previous research efforts that use fault-tree analysis to compute the time required to restore functionality to a facility [31]. Whatever their form, resilience objectives need to be established through a stakeholder-driven process to ensure they align with both societal expectations and broader community resilience goals [34].

The third key input to the proposed framework is the set of criticality factors, as it determines the relative importance of different building components and systems in achieving the global resilience objective. The criticality factors in Figure 5 were chosen primarily using expert opinion. However, a more solid technical foundation for these factors needs to be developed for code development applications. Towards this end, occupants of different types of buildings (e.g., offices, hotels, restaurants, hospitals, schools, etc.) could be surveyed to identify and rank which events are most disruptive to their operations. The results of such surveys could provide the basis for unique sets of criticality factors for different building occupancies, ultimately producing a more appropriate set of performance targets for each occupancy category.

CONCLUSIONS

To address the growing importance of maintaining functionality in ordinary buildings in support of community recovery and resilience, building codes and engineering standards need to expand their historical focus on protecting life safety to include provisions and requirements that aim to prevent damage and minimize loss of functionality. This paper has presented a conceptual framework for deriving a set of risk-consistent performance targets for building components and systems, both structural and nonstructural, from a global resilience objective for the building (e.g., 10% probability of losing functionality in ground shaking with a particular return period). As such, the framework serves as an important tool in the effort to operationalize resilience quantification in the design of buildings under seismic loading. It aims to work within the existing regulatory framework of building codes and engineering standards, ultimately providing risk-consistent foundations for future updates to these documents that not only protect life safety in rare earthquakes but also prevent loss of functionality in more frequent ones.

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