A community-centric approach for developing seismic performance targets for buildings and lifelines

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ABSTRACT: Historically, seismic design provisions have been formulated from the perspective of individual buildings, with a primary goal of minimising fatalities, not preventing damage or loss of functionality. However, as recent earthquakes have demonstrated, widespread damage to a significant number of buildings can adversely impact a community's ability to maintain essential services and prevent outmigration of residents and businesses. An important task in the effort to enhance the resilience of communities to natural disasters involves rethinking the current approach for defining acceptable levels of seismic performance for individual components within the built environment. This paper discusses issues surrounding this task, focusing in particular on commercial buildings. It begins by defining important concepts and terminology that will be used throughout the rest of the paper. Then it discusses two recent developments that attempt to advance towards a more transparent, comprehensive approach for defining acceptable performance objectives. Last, it describes several outstanding issues that need to be addressed by future research and outlines potential strategies for moving forward.

1 INTRODUCTION

An emerging trend from recent earthquakes is that, notwithstanding a few notable exceptions, most buildings and structures perform in a manner consistent with expectations prescribed in modern building codes. That is, structural and non-structural elements may suffer substantial damage, but the building does not collapse or threaten the immediate life safety of its occupants. Historically, seismic design provisions have been formulated from the perspective of individual buildings, with a primary goal of minimising fatalities, not preventing damage or loss of functionality (ICBO 1997). However, as recent earthquakes have also demonstrated, widespread damage to a significant number of buildings can adversely impact a community's ability to maintain essential services and prevent outmigration of residents and businesses, as it can take months or even years to repair or replace damaged structures. Consequently, performance objectives formulated from the perspective of individual components may be inadequate from a community-resilience perspective.

The traditional approach for defining acceptable levels of seismic performance for buildings (as implemented in most modern building codes) gives inadequate consideration to the full range of potential consequences arising from earthquake-induced damage. Historically, building codes have focused on protecting public health and safety through provisions that aim to prevent major structural failure and collapse (i.e., life safety performance). These provisions, however, do little to limit less severe damage that may render typical buildings (e.g., apartments, offices, shops, factories, schools, etc.) unusable for extended periods of time. Furthermore, the traditional approach implemented in building codes fails to consider the aggregated impact of seismic performance levels on community resilience. For example, a community whose stock of commercial and residential buildings suffers considerable damage that renders even a small portion of them unusable for a year or two following an earthquake may experience debilitating outmigration of residents and businesses.

An important task in the effort to enhance the resilience of communities to natural disasters involves rethinking the current approach for defining acceptable levels of seismic performance for individual components within the built environment. Specifically, it is imperative that performance levels for individual buildings:

1. Advance beyond protecting life safety to consider the social, financial, and environmental impact of earthquake-induced damage (e.g., loss of functionality, downtime, repair costs, displacement, business disruption, etc.)
2. Consider the aggregated impact on community resilience (i.e., performance levels that are in the best interests of both the community and individual building, not just individual building)

This paper discusses issues surrounding both of these goals, focusing in particular on commercial buildings. It begins by defining important concepts and terminology that will be used throughout the rest of the paper. Then it discusses two recent developments that attempt to advance towards the above goals. Last, it describes several outstanding issues that need to be addressed by future research and outlines potential strategies for moving forward.

2 DEFINITIONS

2.1 Resilience

Resilience is commonly defined as the "ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NRC 2012). The built environment (i.e., buildings and lifelines) plays a crucial role in enabling a community to successfully function, providing the physical foundations for much of the economic and social activities that characterise a modern society (O'Rourke 2007). Consequently, the performance of the built environment during and after a disaster greatly influences community recovery and resilience, though a resilient community requires not only resilient infrastructure but also resilient social, economic, and political systems (Bruneau et al. 2003, Cutter et al. 2010).

This paper focuses on the built environment and, in particular, commercial buildings and the lifelines that support them. Commercial buildings are especially important to community resilience because the businesses that inhabit them provide both vital services consumed by residents and employment opportunities for the local workforce.

2.2 Functionality

The New Zealand draft building code defines functionality as "the ability of [a] building to continue to serve its purpose for users, including adequate shelter and the provision of services such as sewer and water connections and food preparation and sanitary fixtures" (MBIE 2013). Loss of functionality after a disaster can be caused by many different factors, some of them internal to the building and some external. Internal factors include physical damage to structural elements (beams, columns, braces, shear walls, foundations), architectural finishes (partitions, ceilings, windows, doors, exterior cladding), building services (electrical and lighting, plumbing, sprinklers, HVAC, telecom), and contents (computers, furniture, equipment). External factors include loss of supply from power, water, gas, and/or telecom networks.

In general, loss of functionality depends on the types of components that get damaged, the extent and severity of damage, and the building occupancy. Certain components within a building are more critical to maintaining functionality than others. For example, damage to structural elements like beams and columns, which often support architectural finishes and building services, will likely have greater impact on functionality than damage to HVAC equipment. In addition, damage that is localised but severe in nature will likely have greater impact than widespread, minor damage. Furthermore, two buildings that are damaged to the same degree may have different functionality depending on their occupancy. For example, an apartment building may remain occupiable despite losing power from the grid, whereas an office building that lacks power cannot be occupied (though this will depend on the laws and emergency procedures adopted by a particular community).

Figure 1 presents a fault tree that depicts a highly simplified set of events that could lead to loss of functionality in a commercial building. If any of the four bottom events in the fault tree are realised, the building will lose functionality. Conversely, if none of the events occur (e.g., 5 per cent structural damage, 10 per cent non-structural damage, no loss of power or water), the building will remain functional. There are several things to note in Figure 1. First, non-structural systems include architectural finishes and building services. Second, the structural and non-structural damage thresholds in Figure 1 were chosen somewhat arbitrarily for the purposes of this demonstration and need to be refined using data from previous and future disasters (see Section 4.1 for additional discussion). Third, each event in the fault tree will have varying impact on restoration of functionality, as it will likely take more time to repair structural damage than to restore offsite power.

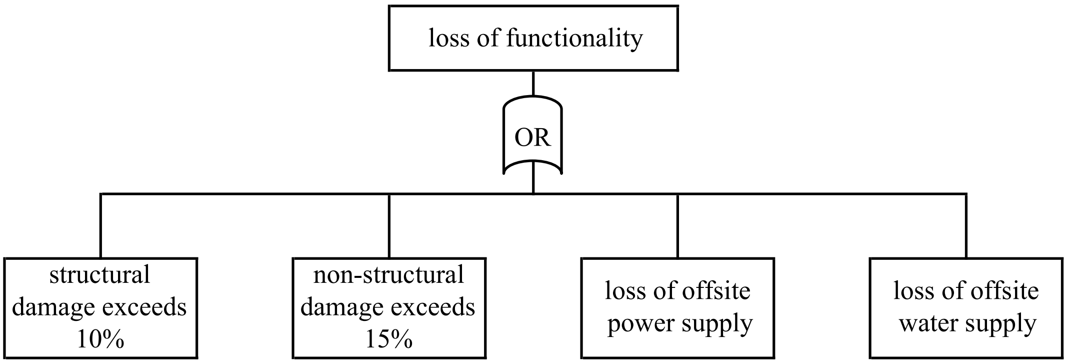

Figure 1. Simple fault tree for loss of functionality in commercial buildings

2.3 Downtime

Downtime refers to the duration of time that a building loses functionality after a disaster. It is influenced by the same factors described in the previous section, including the types of components damaged and the extent and severity of damage. Certain components may be more difficult or costly to repair than others. For example, damage to steel beam-column connections hidden behind architectural finishes will likely be more difficult to repair than damage to lighting systems or exterior cladding. Downtime can be influenced by additional factors, including the finances of the owner or insurer and demand for engineering and construction services, which may be extremely high in a post-disaster environment.

2.4 Reparability

The New Zealand draft building code defines readily repairable as "repairable without relocation of occupants for more than four weeks" (MBIE 2013). Whether a damaged building can be repaired after a disaster depends on many factors, including the specific components that were damaged, the extent and severity of the damage, insurance coverage (if any), and the finances of the owner.

2.5 Business disruption

In commercial buildings, loss of functionality and downtime often result in business disruption. However, the degree of disruption depends on the exact nature of the business. If the business can relocate rapidly or if its employees can work from home in the short term, the impact of loss of functionality and downtime will be lessened. Even if the building is fully functional, factors external to the building can produce business disruption, including:

- Disruption of transportation systems, affecting both shipment of goods and commuting patterns
- Disruption of supply chains (e.g., a factory that supplies a critical input to a business goes down)
- Displacement of workforce or customer base
- Location within a cordon or red zone

The myriad factors that can cause business disruption and affect its duration highlight the interconnectedness of both the built environment and local, regional, national, and global economies, which in turn emphasises the importance of establishing seismic performance targets for commercial buildings that move beyond life safety issues and are consistent with broader community-resilience goals.

3 DISCUSSION

This section briefly describes two recent developments that attempt to advance the two goals described at the end of Section 1 (i.e., moving beyond life safety and considering aggregated impacts). The first development, the latest draft of the New Zealand building code, establishes performance targets for buildings that move beyond life safety. The second development, a community-centric framework developed by Mieler et al. (2013), outlines a methodology for deriving performance targets for individual buildings and lifeline systems that are consistent with community-level resilience goals. The following sections summarise each development.

3.1 New Zealand Building Code draft

In addition to requirements pertaining to life safety and collapse prevention, the latest draft of the New Zealand building code also specifies performance targets for structural and non-structural damage, downtime, and reparability. As such, it represents an important step towards a more complete and transparent consideration of building performance in an earthquake. Because the building code is still in draft, the following discussion will focus on describing the methodology employed rather than commenting on the appropriateness of specific performance targets chosen because they have not been finalised yet.

The most significant change contained in the draft building code involves the introduction of tolerable impact levels. A tolerable impact level (TIL) is a “description of the impact of loads and forces on various aspects of building performance which represent the maximum impact that is tolerable in defined circumstances” (MBIE 2013). In other words, a TIL describes the limits of acceptable performance for a building at a particular hazard level. The draft building code defines seven TILs ranging in impact from insignificant (TIL0) to extreme (TIL6). Each TIL comprises a unique set of performance criteria that address a wide range of building performance issues, including life safety, damage, loss of functionality, and reparability. For example, each TIL has different numerical limits both for the percentage of injuries and deaths among those exposed and for the percentage of structural and non-structural damage (e.g., 2%, 5%, 20%, 40%, etc.). Furthermore, each TIL has different thresholds for downtime (e.g., one day, one week, one month, etc.) and also a specification for the percentage of buildings in each TIL that are expected to be repairable.

Similar to previous versions of the New Zealand building code, the latest draft defines five building importance levels (BILs). These importance levels are used to assign TILs to specific hazard levels. For example, a BIL2 building (which includes typical commercial buildings) might be expected to achieve TIL4 performance or better when subjected to a hazard level with very low likelihood of occurrence in the lifetime of the building (e.g., an earthquake with 475-year return period). More specifically, the draft building code requires that 95 per cent of buildings within a BIL achieve the specified TIL or better. This specification represents an important first attempt at establishing performance expectations for a population of buildings.

While the latest draft of the New Zealand building code takes transparent steps to move beyond life safety, it raises several important issues that require additional research. With respect to the numerical performance criteria associated with each TIL, it is important to use data from recent disasters to develop explicit relationships between the damage percentage and its consequences, including loss of functionality, downtime, and reparability. In addition, it would be useful to engage with community stakeholders and general public to ensure that overall performance levels are indeed acceptable. Lastly, it would be beneficial to analyse the broader impact of the chosen performance criteria on community-level metrics like outmigration of residents, job loss, and disruption to vital public services. These issues represent areas of future research and are discussed in more detail in Section 4.

3.2 **Community-centric framework**

Mieler et al. (2013) propose a framework for linking community-level resilience goals to specific performance targets for individual buildings and lifeline systems. As such, the framework could serve as one possible way to assess the aggregated impact of performance objectives on community resilience. The framework centres on defining undesired outcomes for a community and identifying the vital community functions that need to be maintained in order to prevent the undesired outcomes from occurring after a disaster. For example, one potential undesired outcome might involve a significant outmigration of residents after a disaster. In order to prevent this outcome, the vital community functions that need to be maintained might include housing, employment, education, and basic services like transportation, power, and water (adapted from Cutter et al. 2010, SERRI and CARRI 2009, Twigg 2009, and SPUR 2009).

Once these parameters (i.e., undesired outcomes and vital community functions) have been defined, the framework makes use of event trees to establish a hierarchy of performance objectives for a community and its built environment. This hierarchy begins by specifying performance objectives for a community in terms of the undesired outcomes chosen for consideration: for example, less than 5 per cent probability of significant outmigration after a particular earthquake scenario. Then, using event trees developed for each vital function, performance objectives for each vital community function can be derived from the community-level target. An event tree is a graphical construct that captures the range of possible outcomes for a particular vital community function after an earthquake or other major disturbance. Figure 2 displays a generic example of an event tree for the housing vital community function. Similar trees can be developed for other community functions.

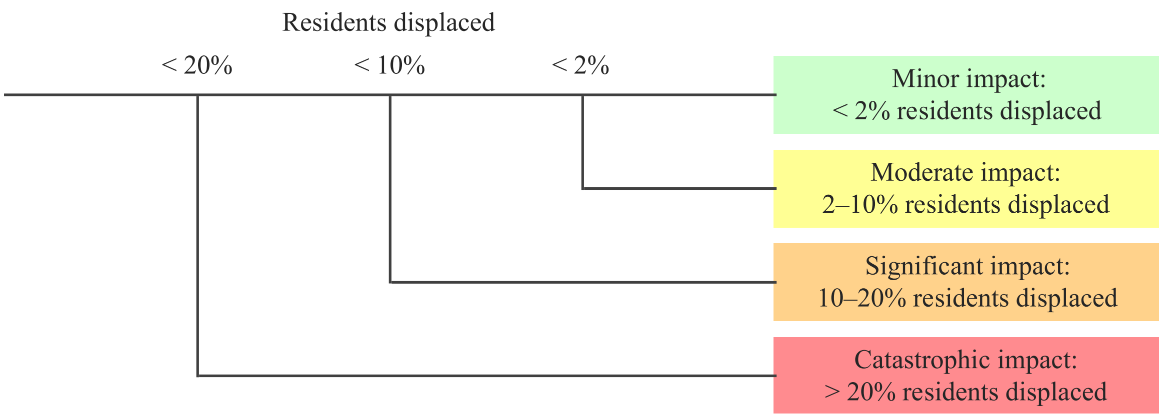

Figure 2. Sample event tree for housing (Mieler et al. 2013)

The event tree in Figure 2 comprises three top events (see the top, left hand side of Figure 2): (1) less than 20 per cent of residents displaced, (2) less than 10 per cent of residents displaced, and (3) less than 2 per cent of residents displaced. At each top event, the event tree splits into two branches. A downward branch indicates failure of the corresponding top event while a horizontal branch indicates success. For example, the downward branch at the first top event in Figure 2 signifies that more than 20 per cent of residents have been displaced. The three top events in Figure 2 delineate and define four distinct outcomes for the housing vital function, the impact of which ranges from minor (less than 2 per cent of residents displaced) to catastrophic (more than 20 per cent displaced). A more detailed description of the proposed framework and event trees can be found in Mieler et al. (2013).

Mieler et al. (2013) also presents a conceptual example that demonstrates how the proposed framework can be used to develop consistent performance targets for individual residential buildings. Table 1 summarises the hierarchy of performance objectives that were developed as part of the example. Though not explicitly demonstrated, the framework can also be used to develop performance objectives for other types of buildings, including commercial buildings. This represents an important area of future research, as these other types of buildings, because of their many potential interdependencies, will require special consideration. For example, an office building will likely require a set of performance targets that address not only the response of the structure itself but also the utilities that its tenants need to run their businesses and organisations successfully.

Table 1. Hierarchy of performance objectives for a community (Mieler et al. 2013)

Entity	Performance objective*
Community	< 1% probability of significant outmigration
Vital functions	*Housing*: < 5% of residents displaced
	Employment: < 9% of businesses disrupted
	Education: < 6% of students displaced
	Public services: < 9% of capacity disrupted
Housing stock	< 5% of residential buildings unsafe to occupy
Residential buildings	< 5% probability of being unsafe to occupy

*Corresponding to an earthquake with 500-year return period.

4 ISSUES

While the two developments described in the previous section mark important advancements towards developing a more robust and transparent approach for defining acceptable seismic performance targets for commercial buildings, many important research tasks and questions remain. The following sections describe several outstanding issues that need to be addressed by future research and outline potential strategies for moving forward.

4.1 Linking damage and its consequences

At the level of individual buildings, it would be beneficial to develop relationships between physical damage and consequences like loss of functionality, downtime, and reparability. These relationships can be used to calibrate the performance criteria for each TIL specified in the latest draft of the New Zealand building code (see Section 3.1). Figure 1 shows a fault tree that graphically depicts a highly simplified relationship between damage (structural, non-structural, loss of power, loss of water) and loss of functionality in a commercial building. As discussed previously, functionality will be lost if any one (or more) of the four bottom events occurs. Though highly simplified, the fault tree in Figure 1 represents a suitable starting point for developing a relationship between damage and functionality. Importantly, the fault tree can be refined and expanded over time as knowledge improves. Similar fault trees can be developed for downtime and reparability.

A crucial component in this task involves establishing appropriate thresholds for structural and non-structural damage above which a building will, for example, lose functionality, experience downtime exceeding six months, or require demolition. Figure 1 assumes a threshold of 10 per cent structural damage and 15 per cent non-structural damage for loss of functionality. In reality, the exact levels will vary depending on the structural and non-structural properties of the building, but as a starting point generic thresholds that cover all types of buildings can be developed.

Data from previous and future disasters will be invaluable in this effort. Following the Christchurch earthquake sequence, a significant number of buildings were inspected after both the September 2010 and February 2011 events using forms similar to the *ATC-20 Rapid Evaluation Safety Assessment Form* (ATC 1995). Data gathered during these inspections include the overall building damage ratio (e.g., none, 0-1%, 2-10%, 11-30%, 31-60%, 61-99%, 100%) and the building tag (e.g., red, yellow, green). If it is assumed that red- and yellow-tagged buildings are not functional, then it is possible to compute a damage threshold above which a building is expected to lose functionality. For example, a building with damage ratio exceeding 10 per cent will likely lose functionality after an earthquake. This number can be refined for different building configurations (e.g., wood-frame, steel moment frame, concrete shear wall, etc.) and occupancies (e.g., residential, commercial, etc.). In addition, similar thresholds can be derived both for reparability and for downtime exceeding a particular duration (e.g., 1 week, 1 month, 6 months, etc.). In order to develop thresholds for downtime, however, additional data pertaining to the evolution of building tags over time are required (i.e., the date a red or yellow tag was issued and the date it was removed). It is unclear whether this data was recorded in Christchurch.

4.2 Evaluating aggregated impacts

At the community level, it would be beneficial to understand the aggregated impacts of performance objectives for individual buildings on metrics like outmigration and job loss. As discussed in Section 3.2, Mieler et al. (2013) outlines a framework for linking community-level resilience goals to specific performance targets for individual buildings and lifeline systems, and also presents a conceptual example that demonstrates how to derive consistent performance targets for residential buildings (see Table 1). An important next step in this effort involves expanding application of the framework to address additional building occupancies (e.g., retail, office, health, education, etc.) and also lifelines in order to produce a more complete hierarchy of performance objectives than shown in Table 1. For example, using the overall target of less than 9 per cent of businesses disrupted, specific performance objectives for commercial buildings can be established (e.g., less than 5 per cent probability of losing functionality). Another important task in this effort involves expanding the derived performance targets for a particular building occupancy from their current form (e.g., less than 5 per cent probability of being unsafe to occupy) to a more comprehensive set of criteria similar to the TILs in the latest draft of the New Zealand building code.

Data from previous and future disasters will be crucial in creating and refining this expanded hierarchy of performance objectives. Damage data for a community's building stock (possibly in the form of the number of green, yellow, and red tags for different building occupancies) can be correlated with community-level metrics like change in population or regional GDP in order to develop predictive relationships for more accurately estimating outmigration or job loss after an earthquake. Once developed, these relationships can be used to calibrate various parts of the framework described in Mieler et al. (2013), all in an effort to ensure that the aggregated impacts of performance objectives for individual buildings are addressed fully. However, before specific performance objectives can be implemented in building codes and engineering standards, it is imperative that community stakeholders and the general public be consulted to ensure that the level of risk associated with the chosen performance objectives is acceptable to the community.

4.3 Developing specific design provisions

The performance criteria specified in the latest draft of the New Zealand building code needs to be translated into specific design provisions that can be used by practicing engineers. This translation will be challenging, as the historical focus of design provisions has been protecting life safety, not limiting damage or preventing downtime. Again, data collected in previous and future disasters will be imperative to this task. For example, data recorded by sensors installed throughout buildings (e.g., the GeoNet Building Instrumentation programme) can be used in conjunction with damage observations to develop thresholds for floor accelerations and inter-story drift ratios above which damage to structural and non-structural systems is expected. These thresholds can be used to translate generic performance criteria in the draft building code (e.g., less than 10 per cent structural damage) into specific acceleration and drift limits for designers (e.g., peak inter-story drift ratios less than 1 per cent).

4.4 Collecting better data

Collecting a more complete and consistent set of data after a disaster, especially over time as the impacted communities rebuild and recover, is a critical component in much of the research described in previous sections. Towards this end, standardised inspection forms like ATC-20 need to be adopted by local, regional, state, and national governments to ensure that data gathered after a disaster is both comprehensive and consistent. Specific information that would be useful includes: building location, structural and non-structural properties, occupancy category, shaking intensity, overall damage ratio, specific damage characteristics (extent and severity of damage to structural/non-structural systems;

access to power, water, sewer, telecom networks; length of disruption), and building tag/status (and its evolution over time). Furthermore, this data needs to be made publically available in a centralised repository or database so that researchers and engineers can use it to advance the state of the practice.

5 CONCLUSIONS

The specific research tasks described in the previous section represent a small portion of the future work required to ensure that performance objectives for individual buildings and lifeline systems are clear, consistent, acceptable, and, ultimately, enhance the resilience of communities to natural hazards. It is crucial that this work be performed in collaboration with a diverse group of researchers, practitioners, and community stakeholders to ensure that the full impact (including social, political, environmental, cultural, and financial implications) of potential performance objectives is considered before being implemented in building codes and design standards. A collaborative, transparent process will also help ensure that performance objectives are both consistent with the expectations of the public and formulated in a way that is most useful to practicing engineers. Ultimately, the set of performance targets that results from this work could provide a common foundation for the current patchwork of codes and standards that govern the design of the built environment, thus ensuring that each important system and component performs in a manner that enhances community resilience.

6 ACKNOWLEDGEMENTS

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