
Seismic resilience vs. Functional recovery of buildings: A critical review

L.Y. Li¹, A. Chang-Richards¹ & M. Boston² & K. Elwood¹

¹The University of Auckland, Auckland.

²The University of Waikato, Auckland.

ABSTRACT

Achieving functional recovery means that buildings can be safely reoccupied in a reasonable amount of time and with minimal repair following a major earthquake. It requires a paradigm shift of building standards and design practice from life-safety-centred to resilience-oriented. This paper presents a critical review of the existing methodologies and frameworks for assessing buildings' seismic resilience and modelling functional recovery. In particular, the insights about how seismic resilience contributes to functional recovery and vice versa were drawn from a comparison of these two concepts. This paper can be helpful in future research to determine the resiliency targets and identify the missing gaps to formulate a framework for functional recovery to be used in the New Zealand engineering and building sector.

1 INTRODUCTION

Buildings have a pivotal role in providing functionality and services for society. While life safety remains an objective of seismic design for buildings, the building codes in many countries such as New Zealand do not consider the level of functionality of buildings following an earthquake (Cere et al. 2017; ICC 2018; Panagiotou 2019; Sattar 2021). Whether a building system can remain functional, however, has been an engineering concern. The demolition of 1,240 buildings (Gates 2015) in the CBD of Christchurch following the February 2011 earthquake and the consequent economic and social disruptions (Kim et al. 2017) had been a wake-up call for most engineers to consider building safety and functionality in a new resilience domain. It has also demonstrated the impact of the lack of consideration for how the functionality of buildings, businesses, and communities will recover after an earthquake (Chang 2014; Marquis et al. 2017). Learning from past disaster events, increased attention has been placed on how the damaged buildings will return to function after a major earthquake (Poland 2014; Wellington City Council 2017a, 2017b). Such a return to function requires buildings to be designed with explicit consideration of not only safety but also repair and recovery time (EERI 2019). Toward this end, over the past two decades, policymakers have been advocating for better-performing buildings to improve their seismic resilience before and after earthquakes (AIJ 2019; The Parliament of New Zealand 2021; The White House 2016). For illustrative purposes, the concept of seismic resilience can be defined as the community's ability to contain the effects of an earthquake and achieve a timely recovery (Burton et al. 2016).

In addition, the concepts of reoccupancy and functional recovery have been recently introduced to support resilience goals at the community level. A considerable amount of literature has been published to address the role of functional recovery in recovery-based design, highlighting safe occupancy and the restoration of building components and services to support the intended functionalities (Cimellaro et al. 2010; EERI 2019; Hassan and Mahmoud 2019; Lin Peihui 2019; Liu et al. 2016; Terzic and Villanueva 2021; Terzic et al. 2021). Notably, FEMA's report P-2090/ NIST SP-1254 provided recommendations for improving the built environment toward post-earthquake reoccupancy and functional recovery (Sattar 2021), which will be efficient tools in realising seismic resilience goals in the future. For brevity, the notion of functional recovery is becoming a pivotal element that makes seismic resilience goals more achievable.

While policy-makers, engineers, and academia have been supporting the consideration of functional recovery in seismic design, there is a lack of technical understanding, methods, and tools for implementation in different contexts (Sattar 2021). In particular, little is known about how functional recovery can be used to achieve resilience goals and what're the differences between the current widely used term-seismic resilience and the relatively new concept-functional recovery, and what are the existing methodologies that quantify both seismic resilience and functional recovery. Toward this end, a critical review of literature on functional recovery and seismic resilience is needed. Through reviewing and comparing the definitions and quantification methodologies in terms of functional recovery and seismic resilience, it is hoped that the review serves as a snapshot and a reference point for those who want to consider functional recovery in seismic design and select the most appropriate methodology to benchmark the performance of a building.

The remaining part of the paper proceeds as follows: Section 2 is an exemplary description of the research methodology where the summarised selected results are presented; Section 3 demonstrates the definitions of seismic resilience and functional recovery; Section 4 offers the primary modelling frameworks and methods of seismic resilience and functional recovery. Section 5 contains some conclusions plus some ideas for further work.

2 RESEARCH METHODOLOGY

Since a critical scientific review should incorporate resources from all available platforms and databases, publications, and unpublished works, it is imperative to access all available documents. In order to include all resources, the search strategy was set as (functional recovery) AND (disaster), and (seismic resilience) AND (disaster) respectively, and the primary inclusion criteria for selecting resources were as follows:

1. When searching for publication resources, databases like Scopus, Web of Science Core Collection, Engineering Village, ASCE Library, and Science Direct are used in this paper. As for unpublished works, such as reports, seminar summaries, official guidelines, bills, and documents, are all included. These unpublished works were mainly developed by some reputable organisations such as the Applied Technology Council (ATC), FEMA, International Code Council (ICC), EERI, NEHRP, NIST, Structural Engineers Association of California (SEAOC), and the QuakeCoRE.
2. Publications are only included in the analysis if it is in the English language. Non-English resources are not included in this review.
3. Only the publications that are relevant for conceptualising seismic resilience and/or functional recovery of buildings, existing methodologies, and frameworks for assessing them have been selected and included in the review.
3. All resources related to seismic resilience and functional recovery are limited in the field of disaster and engineering. Specifically, the research objective is to buildings; lifeline infrastructure systems are not paid much attention here.

4. Articles with high citation rates considered more critical would be analysed in detail.

After applying the search strategy and inclusion criteria, 72 papers were selected for writing up this current review.

3 DEFINITION OF SEISMIC RESILIENCE AND FUNCTIONAL RECOVERY

3.1 Seismic resilience

In accordance with the commonalities and similarities of concepts, the definitions of seismic resilience can be categorised into three groups based on the dimensions of time, functionality, and impetus. As indicated in Figure 1.

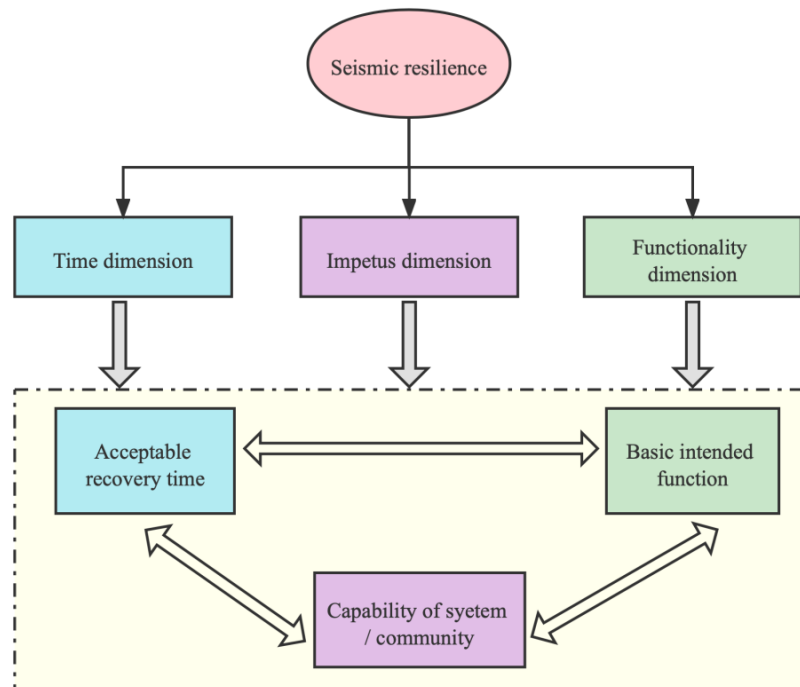


Figure 1: Conceptual definition of seismic resilience

Group 1: From the perspective of functionality dimension

In brevity, functionality can be described as a measure of how well a building or lifeline infrastructure system operates, delivers its required services, or meets its intended purpose (Sattar 2021). With this idea in mind, the most prominent finding to emerge from studies is that a primary objective of seismic resilience of a structure is to provide essential intended functions both before and after disruptive events (Cimellaro 2006). From this standpoint, seismic resilience can be defined as the ability of a building to restore or maintain functionality in the aftermath of an earthquake event (Allenby and Fink 2005; Bruneau 2003; Mokhtari and Naderpour 2020; Tirca et al. 2016).

Group 2: From the perspective of the impetus dimension

In defining seismic resilience, it is natural to think about who should provide the impetus for a building to be resilient and reduce the possibilities of performance failure. Interestingly, many studies on building seismic resilience have highlighted the role of communities and their capabilities (Allenby and Fink 2005; Bruneau and Reinhorn 2007; Burton et al. 2016; Comfort 1999; Haimes 2009; Holmgren 2007; Timmerman 1981;

Paper 0082 –Seismic resilience vs. Functional recovery of multi-story buildings: A critical...

Vugrin et al. 2010). As such, seismic resilience can be described as the ability of communities (at a community level) or systems (at a building system level) to withstand and recover from disruptive incidents.

Group 3: From the perspective of the time dimension

As noted earlier, the requirement for achieving seismic resilience is beyond the basic expectation of achieving life safety. Extensive research has proved the necessity of incorporating the dimension of time in designing recovery-based building codes (Bonowitz 2020; Buckalew 2020; Cimellaro et al. 2010; Cimellaro et al. 2016; De Iuliis et al. 2019; Guidotti et al. 2016; Hassan et al. 2020; Kammouh et al. 2019). Of this, seismic resilience can be defined as the ability of a building to protect life safety, avoid major structural and non-structural failures, and recover functionality within an acceptable amount of time after an earthquake (Burton et al. 2016; Mieler 2016; Miles and Chang 2006). As a matter of fact, the greatest manifestation of community well-being in post-earthquake also relies on the length of recovery time. Extensive downtime of buildings and infrastructure has been found to worsen mental health issues post-earthquake, leading to increased depression, irritability, and resistance (L. Li et al. 2020), which could, in return, add to the complexity of recovery and burden social stability.

3.2 Functional recovery

Drawing upon all available resources, we found that the concept of functional recovery has been defined uniformly in literature, reports, official guidance. Several interesting points noted in the literature about the definition of functional recovery are summarised as follows.

1. Functional recovery can be described as a kind of performance state. It is more than reoccupancy but less than full functionality (Bonowitz 2011; California Legislature 2019; NIST 2016a; Sattar 2021).
2. Functional recovery is an attributor of the individual building; that is, it refers to the performance of a distinct piece of the built environment (FEMA 2018a; NIBS 2019b). In this case, the objective of functional recovery is applied at the individual building or lifeline infrastructure system level.
3. Functional recovery focuses on natural hazards (FEMA 2018a; NIST 2016a; NRC 2012), such as an earthquake.
4. Functional recovery focuses on function, not just safety. It aims to support some basic intended functions and associated services (Bonowitz 2011; California Legislature 2019; Davis 2019; EERI 2019; Sattar 2021).
5. Functional recovery can be measured by functional recovery time T_{FR} , where T_{FR} can be different for various building use and occupancies or lifeline services.

In this paper, we define ‘functional recovery’ of a building as a performance state where a building is maintained or restored to support the intended functions that are determined on the basis of pre-earthquake use or the pre-earthquake specified service level (Bonowitz 2011; California Legislature 2019; Davis 2019; EERI 2019; ICC 2019; Sattar 2021).

4 METHODOLOGIES AND FRAMEWORKS

4.1 Frameworks and quantification methods of seismic resilience

The literature regarding assessing seismic resilience can be divided into two categories, including quantitative and qualitative methodologies. The detailed information can be found in the Appendix (Table 1). It is to be noted only last two literature in Table 1 are qualitative methodologies, while most research belong to quantitative category.

4.1.1 Existing methodologies and tools

According to Table 1, some methodologies developed by agencies and institutions, such as PBEE, FEMA P-58, and REDi, should be clarified first due to their wide application in subsequent methodologies, as they support various analyses such as damage analysis, fragility analysis, and components response analysis. The calculated results can be used directly or indirectly in other models in quantifying seismic resilience. Common assessment tools for estimating performance using assembly-based seismic vulnerability method to generate probable loss estimates include the Performance Assessment Calculation Tool (PACT), the Seismic Performance and Loss Assessment tool (SLAT), and the Seismic Performance Prediction tool (SP3) (Applied Technology Council 2012). Particularly, SP3 and PACT predict possible damage to a building, repair time, repair cost, and the probability of unsafe placarding, while SLAT only focuses on repair cost (Kahandawa R 2020).

4.1.2 Quantitative methodologies of seismic resilience

In this category, methodologies can be further divided into three types: 1) functionality-oriented, 2) probability-oriented, and 3) resilience function-oriented. The functionality-oriented methodologies included such as the damage ratio assessment model-based framework (Fu et al. 2021), the functionality-based framework (Z. Li et al. 2020), and the city-scale time–history analysis-driven framework (Xiong et al. 2020), all of which are aimed to capture the changes of functionality in the aftermath of an earthquake, and generate the corresponding functionality curve or recovery curve of a building.

The probability-oriented frameworks, however, are developed to reveal the probabilistic characteristics of quantification frameworks regarding seismic resilience, including such as the integrated approach (Bruneau and Reinhorn 2007), the probabilistic framework (Henry et al. 2016), the reliability-based approach (Bonstrom and Corotis 2016), and a framework based on stochastic formulation (Neetesh 2017). Probability-oriented frameworks usually determine damage-related factors (e.g., irreparable damage, ground motion intensity) first, then according to relating probability, predict the uncertainty to functionality status or damage status, reflecting this correlation in the recovery path if possible. Notably, the Monte Carlo simulation and Markov-type process are often applied to reduce errors regarding uncertainties resulting from the complex modelling process (Dhulipala 2020; Hutt 2016). The resilience function-oriented methodologies, on the other hand, quantify seismic resilience through an absolute term. With an absolute expression of resilience function, the resilience index and functionality curves can be obtained with available data (Cimellaro 2006; Cimellaro et al. 2010). However, the calculated resilience value cannot provide much suggestive information to decision-makers because this result can be from various combinations of system functionality states and recovery time (Bruneau 2003).

4.1.3 Qualitative frameworks of seismic resilience

Qualitative frameworks aim to provide an understanding of various factors and measures contributing to the overall building performance. On the one hand, these frameworks try to determine the extent to which different system units are resilient, and some performance criteria are introduced to evaluate various measures (Bruneau 2003); On the other hand, these frameworks want to incorporate all characteristics that affect resilience (Cimellaro et al. 2021; Cimellaro et al. 2016). Such frameworks are instrumental in evaluating the overall effect resulting from earthquakes.

4.2 Frameworks and methodologies of functional recovery

Through analysing the existing functional recovery frameworks, we group them into two categories, namely 1) dependent models and 2) independent models. The existing frameworks are summarised in Appendix (Table 2).

The dependent frameworks are defined as relying on existing tools or methodologies (e.g., PBEE, FEMA P-58, REDi) as part of quantification, it requires the use of other existing tools or frameworks to provide particular results in the process of quantifying functional recovery, while the independent models often incorporate mathematical theories and specific engineering knowledge to assess a building's functionality. With such frameworks, the uncertainties of structural and non-structural damage states and their functional states of buildings in the whole recovery process can be handled more efficiently from a mathematical point of view, thereby increasing the reliability of the generated results (P. Lin and Wang, N. 2017; P. H. Lin and Wang, N. Y. 2017).

4.3 Discussion

There are a large number of methods with a view to identifying the changes to the functionality of a building over time or quantifying the functionality within a probabilistic framework. Regardless of the type of methods used, both functional recovery and seismic resilience emphasise the functionality of a building. In comparison, quantification of seismic resilience and functional recovery share commonalities in that they both have consistently used some performance indexes, such as repair time and mobilisation time. The only difference is that the quantification of seismic resilience often involves more indexes, such as the economic cost, repair cost, casualties, and unsafe placarding. Therefore, it seems that to quantify seismic resilience, one would need to include the quantification of functional recovery. In essence, the quantification of seismic resilience and functional recovery involves the consideration of the building's capacity, and the most significant difference comes from the requirement of functionality level. From this standpoint, the quantification of seismic resilience is more comprehensive that should cover the whole recovery process, from the occurrence of the hazard to the completion of repair activities, while the quantification of functional recovery is focused on specific functionality levels, which should be beyond occupancy and less than full functionality (Mieler and Mitrani-Reiser 2018).

Moreover, it is found that existing methodologies (e.g., FEMA P-58, REDi, PBEE) play an essential role in the quantification of both seismic resilience and/or functional recovery as they could provide various analysis results. However, it has to be noted that the existing tools can only give an approximate result due to their lacked optimisation ability for each actual earthquake event. For instance, it is feasible to use the PACT, SLAT, and SP3 to obtain the approximate repair cost assessment. However, these tools are not specifically used for post-earthquake repair cost estimation, as some of the factors that affect the repair cost may not be previously considered in the assessment.

5 CONCLUSIONS

Seismic resilience and functional recovery provide us with a solution to a more resilient community. This paper reviewed a range of definitions and methodologies regarding seismic resilience and functional recovery in the existing literature and practical applications. The definition of seismic resilience encompasses three dimensions -time, impetus, and functionality. In contrast. Functional recovery can be regarded as a performance state where a building is maintained or restored to support the intended functions that are determined based on pre-earthquake use or the post-earthquake specified service level. It is to be noted that though both functional recovery and seismic resilience focus on functionality, seismic resilience involves several time milestones, such as reoccupancy time, functional recovery time, full functionality time, while functional recovery can be generally measured by functional recovery time.

Furthermore, this paper found the modelling framework for functional recovery can be viewed as a part of the quantification of seismic resilience as the performance measures involved in functional recovery are all included in the quantification of seismic resilience, which can also be concluded from its definitions. Moreover, the quantifying frameworks of seismic resilience show their resemblance with functional recovery

Paper 0082 –Seismic resilience vs. Functional recovery of multi-story buildings: A critical...

in capturing the change of a building's functionality status over time. Thus, it is feasible to construct functionality-related models with hazard analysis, damage analysis, and structural analysis to quantify seismic resilience or functional recovery.

According to findings from this review, when designing the framework for functional recovery in the future, the expected performance should be determined in a much broader social context. Notably, the interdependency between an individual building and its adjacent infrastructure system should be considered at the community level. In the current frameworks, the index used in damage analysis and building response analysis should also be determined consistently to be more applicable regarding various hazard levels and building types.

6 ACKNOWLEDGEMENT

The first author would like to thank the China Scholarship Council for providing the CSC scholarship to perform this PhD research. In addition, this research stems from the QuakeCoRE IP1 project.

7 REFERENCES

- AIJ. 2019. "Towards a proposal of resilience and Business Continuity Performance (BCP) level for evaluating the performance of building functionality preservation and recovery after natural disasters." In 2019 AIJ Annual Meeting. Kanazawa, Japan: Architectural Institute of Japan, Special survey committee on resilience and BCP.
- Allenby, B., and Fink, J. 2005. 'Toward inherently secure and resilient societies', *Science*, 309: 1034-36.
- Applied Technology Council. 2012. "Seismic performance assessment of buildings volume 1 - Methodology (FEMA P-58-1)." In. Washington, DC.
- Bonowitz, David. 2011. "Resilience Criteria for Seismic Evaluation of Existing Buildings." In A 2008 Special Projects Initiative Report. San Francisco, California: Structural Engineers Association of Northern California.
- Bonowitz, David. 2020. "Functional recovery- What it means to design for community resilience." In 2020 National Earthquake Conference. San Diego, California: EERI Distinguished Lecture.
- Bonstrom, H., and Corotis, R. B. 2016. 'First-Order Reliability Approach to Quantify and Improve Building Portfolio Resilience', *Journal of Structural Engineering*, 142: 12.
- Bruneau, M., and Reinhorn, A. 2007. 'Exploring the concept of seismic resilience for acute care facilities', *Earthquake Spectra*, 23: 41-62.
- Bruneau, M.; Chang, S. E.; Eguchi, R. T., et al. 2003. 'A framework to quantitatively assess and enhance the seismic resilience of communities', *Earthquake Spectra*, 19: 733-52.
- Buckalew, J., Bonowitz, D., Mayer, R., et al. 2020. "Understanding community resilience and functional recovery." In.: SEAOC Resilience Committee.
- Burton, H. V., Deierlein, G., Lallemand, D., et al. 2016. 'Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience', *Journal of Structural Engineering*, 142: 1-11.
- California Legislature. 2019. "AB-393 Building codes: earthquake safety: functional recovery standard." In AB-393 Building codes, 5.
- Cere, G., Rezgui, Y., and Zhao, W. Q. 2017. 'Critical review of existing built environment resilience frameworks: Directions for future research', *International Journal of Disaster Risk Reduction*, 25: 173-89.

- Chang, S.E., Taylor, J.E., Elwood, K.J., Seville, E., Brunsdon, D., Gartner, M. 2014. 'Urban Disaster Recovery in Christchurch: The Central Business District Cordon and Other Critical Decisions', *Earthquake Spectra*, 30: 513-32.
- Cimellaro, G. P., Arcidiacono, V., and Reinhorn, A. M. 2021. 'Disaster Resilience Assessment of Building and Transportation System', *Journal of Earthquake Engineering*, 25: 703-29.
- Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. 2010. 'Framework for analytical quantification of disaster resilience', *Engineering Structures*, 32: 3639-49.
- Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. 2006. "Quantification of seismic resilience." In *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*. San Francisco, California, USA.
- Cimellaro, G. P., Renschler, C., Reinhorn, A. M., et al. 2016. 'PEOPLES: A Framework for Evaluating Resilience', *Journal of Structural Engineering*, 142: 13.
- Comfort, L. K. 1999. *Shared risk : complex systems in seismic response* (Pergamon: Amsterdam).
- Davis, C.A. 2019. "Infrastructure System Resilience: Functionality and Operability." In *2nd International Conference on Natural Hazards & Infrastructure (ICONHIC 2019)*. Chania, Greece.
- De Iuliis, M., Kammouh, O., Cimellaro, G. P., et al. 2019. 'Downtime estimation of building structures using fuzzy logic', *International Journal of Disaster Risk Reduction*, 34: 196-208.
- Dhulipala, Somayajulu L. N. 2020. 'Dysfunctionality hazard curve- Risk-based tool to support the resilient design of systems subjected to multihazards', *Journal of Risk and Uncertainty in Engineering Systems*, 7: 1-35.
- EERI. 2019. "Functional Recovery: A Conceptual Framework with Policy Options." In, 1-13. Oakland, California: Earthquake Engineering Research Institute.
- FEMA. 2018a. "Seismic Performance Assessment of Buildings, Methodology and Implementation." In. Washington, D.C.: the Applied Technology Council for the Federal Emergency Management Agency.
- Fu, Z. J., Gao, R., and Li, Y. M. 2021. 'Measuring seismic resilience of building portfolios based on innovative damage ratio assessment model', *Structures*, 30: 1109-26.
- Furley, Jace, van de Lindt, John W., Pei, Shiling, et al. 2021. 'Time-to-Functionality Fragilities for Performance Assessment of Buildings', *Journal of Structural Engineering*, 147.
- Gates, C. 2015. '1240 central Christchurch buildings demolished', *Stuff*. <https://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/66290638/1240-central-christchurch-buildings-demolished>.
- Guidotti, R., Chmielewski, H., Unnikrishnan, V., et al. 2016. 'Modeling the resilience of critical infrastructure: the role of network dependencies', *Sustainable and Resilient Infrastructure*, 1: 153-68.
- Haimes, Yacov Y. 2009. 'On the definition of resilience in systems', *Risk Analysis*, 29: 498-501.
- Hassan, E. M., and Mahmoud, H. 2019. 'Full functionality and recovery assessment framework for a hospital subjected to a scenario earthquake event', *Engineering Structures*, 188: 165-77.
- Hassan, E. M., Mahmoud, H. N., and Ellingwood, B. R. 2020. 'Resilience of School Systems Following Severe Earthquakes', *Earths Future*, 8: 1-19.
- Henry, V. Burton, Gregory, G. Deierlein, David, Lallemand, et al. 2016. 'Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience', *Journal of Structural Engineering-Asce*.
- Holmgren, Åke J. 2007. 'A Framework for Vulnerability Assessment of Electric Power Systems.' in, *Critical Infrastructure* (Springer: Berlin).
- Paper 0082 –Seismic resilience vs. Functional recovery of multi-story buildings: A critical...*

- Hutt, C. M.; Almufti, I.; Willford, M.; Deierlein, G. 2016. 'Seismic Loss and Downtime Assessment of Existing Tall Steel-Framed Buildings and Strategies for Increased Resilience', *Journal of Structural Engineering*, 142: 17.
- ICC. 2018 "International Existing Building Code (IEBC)." In *International Existing Building Code (IEBC)*. Country Club Hills, Illinois: International Code Council.
- ICC, CALBO. 2019. "A national approach to seismic functional recovery for new constructions." In. California State Capitol in Sacramento.
- Kahandawa R, Domingo N, Chawynski G, et al. 2020. 'Factors impacting post-earthquake damage repair cost estimations', *International Journal of Disaster Resilience in the Built Environment*, 12: 29-49.
- Kammouh, O., Noori, A. Z., Cimellaro, G. P., et al. 2019. 'Resilience Assessment of Urban Communities', *Asce-Asme Journal of Risk and Uncertainty in Engineering Systems Part a-Civil Engineering*, 5: 17.
- Kim, J. J., Elwood, K. J., Marquis, F., et al. 2017. 'Factors Influencing Post-Earthquake Decisions on Buildings in Christchurch, New Zealand', *Earthquake Spectra*, 33: 623-40.
- Li, L., Reinhardt, J. D., Pennycott, A., et al. 2020. 'Prevalence of and Risk Factors for Depression Among Older Persons 6 Months After the Lushan Earthquake in China: A Cross-Sectional Survey', *Frontiers in Psychiatry*, 11.
- Li, Zaishang, Li, Nan, Cimellaro, Gian Paolo, et al. 2020. 'System Dynamics Modeling-Based Approach for Assessing Seismic Resilience of Hospitals: Methodology and a Case in China', *Journal of Management in Engineering*, 36: 1-44.
- Lin, P. H., and Wang, N. Y. 2017. 'Stochastic post-disaster functionality recovery of community building portfolios I: Modeling', *Structural Safety*, 69: 96-105.
- Lin, Peihui, and Wang, Naiyu. 2017. 'Stochastic post-disaster functionality recovery of community building portfolios II: Application', *Structural Safety*, 69: 106-17.
- Lin Peihui, Wang Naiyu. 2019. "A probabilistic framework for post-disaster functionality recovery of community building portfolios." In *13th International Conference on Applications of Statistics and Probability in Civil Engineering*, 1-8. Seoul, South Korea.
- Liu, M., Giovinazzi, S., and Beukman, P. 2016. 'Post-earthquake performance indicators for sewerage systems', *Proceedings of the Institution of Civil Engineers-Municipal Engineer*, 169: 74-84.
- Marquis, F., Kim, J. J., Elwood, K. J., et al. 2017. 'Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand', *Bulletin of Earthquake Engineering*, 15: 731-58.
- Masoomi, Hassan, Burton, Henry, Tomar, Agam, et al. 2020. 'Simulation-Based Assessment of Postearthquake Functionality of Buildings with Disruptions to Cross-Dependent Utility Networks', *Journal of Structural Engineering*, 146: 1-13.
- Mieler, M. W., and Mitrani-Reiser, J. 2018. 'Review of the State of the Art in Assessing Earthquake-Induced Loss of Functionality in Buildings', *Journal of Structural Engineering*, 144.
- Mieler, M. W.; Uma, S. R.; Mitrani-Reiser, J. . 2016. 'Using failure analysis tools to establish seismic resilience objectives for building components and systems', *Bulletin of the New Zealand Society for Earthquake Engineering*, 49: 86-96.
- Miles, S. B., and Chang, S. E. 2006. 'Modeling community recovery from earthquakes', *Earthquake Spectra*, 22: 439-58.
- Mokhtari, M., and Naderpour, H. 2020. 'Seismic resilience evaluation of base-isolated RC buildings using a loss-recovery approach', *Bulletin of Earthquake Engineering*, 18: 5031-61.
- Neetesh, S.; Armin, T.; Paolo, G. 2017. 'Resilience analysis: a mathematical formulation to model resilience of engineering systems', *Sustainable and Resilient Infrastructure*, 3: 49-67.
- Paper 0082 –Seismic resilience vs. Functional recovery of multi-story buildings: A critical...*

- NIBS. 2019b. "Resource Paper: Resilience-Based Design and the NEHRP Provisions." In. Washington, D.C.: the National Institute of Building Sciences, Building Seismic Safety Council for the Federal Emergency Management Agency.
- NIST. 2016a. "Community Resilience Planning Guide for Buildings and Infrastructure Systems." In NIST Special Publication 1190. Gaithersburg, Maryland: National Institute of Standards and Technology.
- NRC. 2012. "Disaster Resilience: A National Imperative." In. Washington, D.C.: National Research Council.
- Panagiotou, M. 2019. "Earthquake Resilience and Functional Recovery of Buildings in the United States: Problem Statement and Technical Solutions." In.: Online School of Earthquake Resilient Design.
- Poland, Chris. 2014. "A Framework for Creating Disaster Resilient Communities." In 10th US National Conference on Earthquake Engineering, Anchorage, Alaska.
- Sattar, S.; Ryan, K.; Arendt, L., et al. 2021. "Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time." In NIST-FEMA Special Publication FEMA P-2090/NIST SP-1254, 1-115. Gaithersburg, MD: National Institute of Standards and Technology.
- Terzic, V., Kolozvari, K. 2020. "Evaluation of Post-earthquake Functional Recovery for a 42-Story Building Located in Los Angeles." In Proceedings of the 2020 Los Angeles Tall Buildings Structural Design Council Conference, 93-113. Los Angeles, California: Los Angeles Tall Buildings Structural Design Council
- Terzic, V., and Villanueva, P. K. 2021. 'Method for probabilistic evaluation of post-earthquake functionality of building systems', *Engineering Structures*, 241.
- Terzic, V., Villanueva, P. K., Saldana, D., et al. 2021. 'Framework for modelling post-earthquake functional recovery of buildings', *Engineering Structures*, 246.
- The Parliament of New Zealand. 2021. "Building (Building Products and Methods, Modular Components, and Other Matters) Amendment Act 2021." In Building (Building Products and Methods, Modular Components, and Other Matters) Amendment Act (2021/21), 75.
- The White House. 2016. 'Executive Order: Establishing a Federal Earthquake Risk Management Standard'. <https://obamawhitehouse.archives.gov/the-press-office/2016/02/02/executive-order-establishing-federal-earthquake-risk-management-standard>.
- Timmerman, Peter. 1981. 'Vulnerability, Resilience and the collapse of society: A review of models and possible climatic applications', *Journal of Climatology*, 1: 396.
- Tirca, L., Serban, O., Lin, L., et al. 2016. 'Improving the Seismic Resilience of Existing Braced-Frame Office Buildings', *Journal of Structural Engineering*, 142.
- Vugrin, E. D., Warren, D. E., Ehlen, M. A., et al. 2010. 'A Framework for Assessing the Resilience of Infrastructure and Economic Systems', *Sustainable and Resilient Critical Infrastructure Systems: Simulation, Modeling, and Intelligent Engineering*: 77-116.
- Wellington City Council. 2017a. "Wellington Resilience Strategy." In, 1-59. Wellington, New Zealand: Wellington City Council.
- Wellington City Council. 2017b. 'Wellington unveils its comprehensive urban resilience strategy to prepare the city for the next 100 years', Accessed 15 March <https://wellington.govt.nz/news-and-events/news-and-information/our-wellington/2017/03/resilience-strategy>.
- Xiong, C., Huang, J., and Lu, X. Z. 2020. 'Framework for city-scale building seismic resilience simulation and repair scheduling with labor constraints driven by time-history analysis', *Computer-Aided Civil and Infrastructure Engineering*, 35: 322-41.

8 APPENDIX

Table 1 Existing methodologies and frameworks for assessing seismic resilience of buildings.

Methodology	Description	Source
Performance-Based Earthquake Engineering (PBEE) methodology	PBEE focuses on the probabilistic calculation of meaningful system performance measures to facility stakeholders by hazard analysis, structural analysis, damage analysis, and loss analysis.	Pacific Earthquake Engineering Research (PEER)
The Resilience-based Earthquake Design Initiative (REDi™) rating system	REDi™ evaluates downtime and direct repair cost by introducing repair class, and impeding factors.	Arup's Advanced Technology and Research team
FEMA P-58	This methodology combines ground motion hazard and structural response to make predictions of component-level damage and its associated consequences, which are defined in terms of repair costs, repair time, casualties, and building tagging.	The Applied Technology Council (ATC), and FEMA
Framework based on the damage ratio assessment model	This framework is designed to estimate the building-level functionality, where it considers repair cost, economic loss, repair time, downtime, casualties, and unsafe placarding.	(Fu et al. 2021)
A probabilistic approach	This framework generates fragility curves through the limit states and ground motion intensity, and produces the final probabilistic assessment of recovery of functionality at the building level.	(Henry et al. 2016)
A reliability-based approach	This approach applies the first-order reliability method (FORM) to evaluate the probability distribution of resilience for a suite of spatially distributed buildings.	(Bonstrom and Corotis 2016)
Resilience function	This method quantifies resilience in an absolute term with considerations of damage, response, and recovery.	(Cimellaro 2006; Cimellaro et al. 2010)
A framework based on stochastic formulation	This framework evaluates the completion time of the recovery steps and the occurrence time of disrupting shocks, and predicts the system state after the completion of each recovery step.	(Neetesh 2017)
The city- scale time– history analysis-driven framework	This method quantifies building seismic resilience and achieves repair scheduling with repair resource constraints.	(Xiong et al. 2020)
The functionality-based framework	This framework uses a system dynamics model to simulate a hospital's functionality and assess resilience through the functionality curve.	(Z. Li et al. 2020)
An integrated framework	This framework relates probability functions, fragilities, and resilience in a single integrated approach.	(Bruneau and Reinhorn 2007)

An analytical framework based on system performance criteria	This framework uses a system diagram to illustrate how resilience can be improved through systematic assessment and modification in both pre-earthquake and post-earthquake contexts.	(Bruneau 2003)
PEOPLE framework	PEOPLE framework includes population, environment, organization, physical infrastructure, lifeline, economy, and society.	(Cimellaro et al. 2021; Cimellaro et al. 2016)

Table 2 Existing methodologies and frameworks for assessing functional recovery of buildings.

Methodologies	Tools/frameworks	Description	Sources
A probabilistic, building-level framework	PBEE, FEMA P-58, FTA (Fault Tree Analysis)	This framework uses the building's post-earthquake functionality state and inspection limit state to model functional recovery, and it includes the functionality evaluation model, repair time model, and mobilization model.	(Terzic et al. 2021)
A probabilistic evaluation methodology	PBEE, FEMA P-58, FTA	This method is used for probabilistic evaluation of the post-earthquake building's functionality. It aims to determine the percent of building areas with compromised functionality and identify building components that impair its functionality.	(Terzic and Villanueva 2021)
A model based on time-to-functionality (TTF) fragilities	REDi, FEMA P-58	This methodology uses fragility and consequence functions from FEMA P-58 to generate the TTF fragility curve and produces the reoccupancy and functional recovery TTF fragility curve.	(Furley et al. 2021)
A probabilistic analytical framework towards tall buildings	OpenSees, FEMA P-58	This framework assesses post-earthquake functional recovery of tall buildings. It calculates damage-impaired losses and evaluates recovery process.	(Terzic 2020)
A model based on the time-dependent building functionality	—	This methodology is formulated to quantify post-earthquake functionality by considering both the physical damage to buildings caused by ground shaking and the disruptions to the cross-dependent utilities that support the community.	(Masoomi et al. 2020)
The building portfolio functionality recovery modelling (BPRM) method	—	BPRM uses the discrete state, continuous-time Markov Chain (CTMC) to model individual building-level restoration, and aggregate the CTMC restoration processes of separate buildings across the domain of the community and over the entire recovery time horizon to obtain portfolio-level recovery.	(P. Lin and Wang, N. 2017; P. H. Lin and Wang, N. Y. 2017)