# Post-earthquake functional recovery: A critical review

*S. Zhan[1], A. Chang-Richards[1], M. Boston[2] & K. Elwood[1]*

1. The University of Auckland, Auckland.

2. The University of Waikato, Hamliton.

## ABSTRACT

Functional recovery is not only about resotring buildings damaged from an earthquake event to a certain level of functionality, but also adds to community resilience. This paper aims to provide a critical review of existing research on functional recovery, with a focus on identifying the key factors affecting the restoration of post-earthquake functionality and implications of functional recovery for multi-storey buildings in the New Zealand context. It starts by reviewing research related to post-earthquake building resilience and recovery, followed by a summary of existing methodologies for quantifying functional recovery. The review shows that the factors that affect the process and outcome of functional recovery fall into four categories, namely: 1) seismic resilience of the building itself, 2) availability of resources for building repairs, 3) social and organisational preparedness and 4) governance. It is hoped that the introduction of functional recovery notion and methodology will not only influence the decision making of restoring those damaged buildings with residual capacity after an earthquake, but also will inform the changes in engineering design practice with whole-life cycle functionality taken into consideration.

## 1 INTRODUCTION

Over the past decade, the topic of seismic resilience has attracted attention from scholars and engineers with a focus on preparing our built environment and communities for major earthquake events. In defining to what extent the recovery takes place for a building, the National Earthquake Hazards Reduction Program (NEHRP) in the USA,  suggested three stages of recovery, namely re-occupancy, functional recovery, and full recovery according to the proportion of functionality of a building compared to that before a disaster (Earthquake Engineering Research Institute [EERI], 2019). The concept of functional recovery serves as a link between the retrofit of individual building and community resilience. Therefore, to achieve earthquake-resilient communities, it is essential to define the recovery-based objectives for an individual building in terms of practically acceptable recovery times after certain levels of seismic impacts. It is also essential that different recovery-based objectives are developed to take account of various types of building occupancys and/or lifeline services (FEMA, 2021).

This paper aims to identify the factors reported in literature that affect post-earthquake functional recovery of buildings and infrastructure systems. To achieve this objective, a critical review of the existing methodologies for assessing functional recovery, design guidelines for seismic resilience towards functional recovery, and relevant case studies on applying these frameworks was conducted.

# 2 SEISMIC RESILIENCE AND RECOVERY

## 2.1 Understanding seismic resilience and recovery

The term ‘seismic resilience’ was defined as the ability of a system to reduce the effects of a shock and recover rapidly after the shock (Bruneau et al., 2003). The Earthquake Engineering Research Institute (EERI) summarised the definitions of resilience and recognised some common patterns in these definitions, such as resilience as an attribute of human organisations, primarily about recovery of functions, measured as recovery time, and mitigates shock of natural hazard (EERI, 2020). The concept of community resilience, however, is commonly seen as an attribute of a social unit or organisation in responding to stresses and shocks. A resilient community has the ability to expedite the restoration of critical services and meet its time-based resilience goal for post-earthquake recovery. The resilience of buildings is commonly seen as the building’s ability to restore its functionality (Cimellaro, Reinhorn, & Bruneau, 2010; Earthquake Engineering, 2020).

## 2.2 Quantifying seismic resilience and recovery

Cimellaro, Reinhorn, & Bruneau (2010) introduced a resilience index to quantitatively evaluate the resilience of buildings and such resilience represents the ability of the building to sustain a certain level of functionality often determined by building owners and/or communities . As shown in Figure 1, it is calculated as the normalised area under the recovery curve which is determined by the recovery time and predicted recovery path. The recovery time includes both mobilisation time and repair time with high uncertainties such as varied earthquake intensities, type of buildings and functionality requirements for repair/rebuild, and availability and allocation of resources (Cimellaro et al., 2010). Mobilisation time is the time needed for post-earthquake damage evaluation, site inspection, and relocation of building functions before the actual repair takes place. The repair time, on the other hand, represents the time required for the actual repair process to bring the building to a desired functionality level. Based on the schematic representation of recovery curve in Figure 1, the functionality performance, Q(t) can be mathematically illustrated in Equation 1 which is the area under the recovery curve from the occurrence of the earthquake (T1) to full recovery of functionality (T3).

$$R = \int_{T3}^{T1} [100 - \mathrm{Q(t)}]\mathrm{dt} \qquad (1)$$

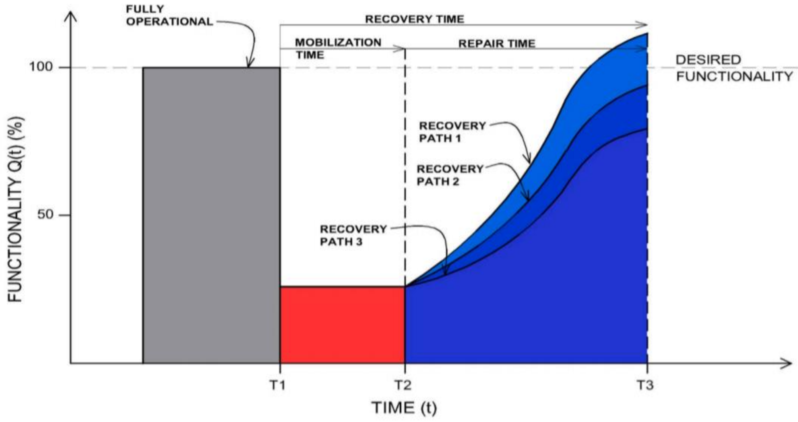

*Figure 1: Post-earthquake recovery curve of functionality*

# 3 POST-EARTHQUAKE FUNCTIONAL RECOVERY

## 3.1 Building functionality and functional recovery

Functionality of a building or a structure was defined in terms of the quality of service which a building provides (Cimellaro et al., 2010) (i.e. hospitals, schools, and power stations etc.) Functionality term can also be used to refer to describe the needed functions of  specific individual systems or components within a building, such as suppression, ventilation, power supply, water supply and fire safety systems (Johnson et al., 1999). In recent years, the notion of functionality has been adapted by the Building Seismic Safety Council (BSSC) and the American Society of Civil Engineers (ASCE) and referred asthe 'availability of a building or facility to be used for its intended purposes' (EERI, 2019).

Loss of functionality in buildings can give rise to multiscale impacts that cascade through a community across space and time, and disrupts important services including housing, sanitation, healthcare, education, and public transit (Mieler & Mitrani-Reiser, 2018). To estimate the indirect losses of damaged buildings due to extensive downtime, Bonowitz (2011) first suggested three post-earthquake recovery states of a building or system according to the functionality level desired, namely i) re-occupancy, ii) functional recovery, and iii) full recovery. The concepts of re-occupancy and functional recovery have been used as critical design targets connecting the design, construction, and retrofit of each building, major lifeline facility systems, and broader community resilience (FEMA, 2021).

## 3.2 Frameworks for modelling functional recovery in multi-storey buildings

To quantify functional recovery of a building, it is important to estimate the mobilisation and repair time for a damaged building (Cimellaro et al., 2010). Accurate repair time estimations can also provide reliable evidence and information for stakeholders to make informed decisions about building repairs. There are attempts to develop a framework for quantify the functional recovery of multi-storey buildings. For instance,  the performance-based earthquake engineering (PBEE) is a probabilistic methodology that provides an assessment framework to quantify relative performance metrics of building recovery (Burton et al., 2016). It is the first framework that has introduced a component-based approach to estimating physical and economic losses. Drawing upon PBEE, FEMA further developed a FEMA P-58 Loss Assessment Methodology which consists of a comprehensive collection of deterministic structural analysis and consequence functions for buildings that have more than 700 structural and non-structural components (FEMA, 2001). Each building component has its unique fragility curve, and a unique consequence function is identified for each damage state within this fragility curve. The overall losses of the building can be calculated by the sum of each component multiplying with the unit costs for each of its damage states from the consequence functions. Monte Carlo simulation can be then performed to realise the uncertainty and variety of ground motion characteristics and component responses (Almufti & Willford, 2013).

Moreover, in 2013 Arup (Almufti & Willford, 2013) proposed the REDi™ framework to assessseismic performances of buildings according to the philosophy of both resilience-based and performance-based design. The assessment criteria include organisational resilience, building resilience, and ambient resilience that are required for a business to be qualified for a REDi™ rating. A loss assessment is also necessary to prove that certain numbers of discretionary recommendations from the REDi™ resilience objectives are also satisfied regarding the post-earthquake financial loss and downtime. The REDi™ roadmap, however, assists the business owners with targeted decisions to re-commerce productions or operations and undertake repairs to their premises rapidly after an earthquake event (Almufti & Willford, 2013).

## 4 FACTORS INFLUENCING THE RESTORATION OF FUNCTIONALITY

Based on the review of literature, this section summarises the major factors that affect the restoration of building functionality after an earthquake event (Table 1). By using content analysis method, we classify these factors into four categories, namely: 1) seismic resilience of the building itself, 2) resource availability for building repairs, 3) social and organisational preparedness, and 4) governance. The description and definition for each factor are explained in detail below.

*Table 1: Factors influencing the restoration of functionality*

| **Category** | **Factor** | **Description/definition** | **Source** |
|---|---|---|---|
| Seismic resilience of the building itself | Severity of damage to building components | The summation of the severity of damage sustained by all components in the building | (Kinugasa & Mukai, 2019; Mieler, M. W. & Mitrani-Reiser, 2018; Terzic, Yoo, & Aryan, 2016) |
| | Type of building materials | The seismic performance of structures varies in different materials | (Alam et al., 2013) |
| | Functionality of a building pre-earthquake | The original purposes and functions of the building or system | (Comerio, 2006; FEMA, 2021) |
| | Interdependence between a building and its lifeline infrastructure systems | The interdependencies and interactions of different infrastructure systems beyond the building footprint | (Cardoni et al., 2020; Earthquake Engineering Research Institute, 2019) |
| | Ability to relocate functions and/or feed through alternatives | The capability to move and maintain operations and services from the damaged building to another safe location during the recovery process | (Bruneau et al., 2003; Comerio, 2006) |
| Resourcing for building repairs | Availability of resources | The availability of repair fundings, building materials, and human resource affecting the functional recovery of buildings in New Zealand | (Balaei et al., 2021; Macaskill & Guthrie, 2018; Marquis et al., 2017; Nguyen & Noy, 2021) |
| | Resource allocation and repair scheduling method | Proper resource allocation plan to eliminate mobilization delays | (Hassan & Mahmoud, 2019; Mieler, M. et al., 2018; Xiong, Huang, & Lu, 2020) |
| Social and organisational preparedness | Organisational networks and organisational capacity | The organisational capacity of local businesses heavily affects the early-stage recovery of the community | (Stevenson et al., 2011; Stevenson et al., 2014) |
| | Social and Community preparedness | The post-earthquake response of a community is affected by the relationships between people and organisations in the social context | (Cretney, 2016; Rivera-Muñoz & Howden-Chapman, 2020; Vallance, 2011) |
| Governance | Roles of Governmental agencies | Establishment of legislative frameworks and recovery approaches by the governmental agencies | (He et al., 2021; Mamula-Seadon & McLean, 2015) |

| | | | |
|---|---|---|---|
| | Multi-organisational communication and collaboration | The communication and collaborations between governmental agencies, affected organisations and residents | (Blake et al., 2019; Botha & Scheepbouwer, 2015; Tagliacozzo, 2018) |

### 4.1 Severity of damage to building components

The severity of building damage certainly plays a role in influencing the post-earthquake functionality level of a building and the amount of restoration work required for recovery (Kinugasa & Mukai, 2019). The severity of earthquake damage to a building can be defined by the summation of the severity of damage sustained by all building components including structural, non-structural, and utility services components (Mieler & Mitrani-Reiser, 2018). Higher severity and larger amounts of building damage likely result in greater demand for resources required for repairs and longer repair time.

### 4.2 Type of building materials

The seismic performance of structures varies in different materials (e.g. masonry, reinforced concrete and timber), and leads to differences in the severity of physical damage to the whole building. According to Alam et al. (2013), the level of difficulty in assessing damagesand repairing the damaged components, to a large extent, depends on the materials and how the components are physically connected to other parts of a building (). Therefore, the repair time and resource demand also vary depending on types of materials used in a building.

### 4.3 Functionality of a building pre-earthquake

The goals of the post-earthquake recovery process often depend on the original functionality of a building before the earthquake (FEMA, 2021). Hence, the original purposes and functions ofa building or a system directly influence the loss of its functionality after the earthquake and determining the nature/types of repair tasks and the timeframes for restoration and recovery. A clear understanding of the functionalities between different components of a building or system would benefit the restoration of functionality by speeding up the decision making process. Different categories of building occupancy (i.e. office, retail, educational, governmental, or healthcare institutions) will pose different impeding factors for functional recovery (Comerio, 2006).

### 4.4 Interdependence between a building and its lifeline infrastructure systems

The functional recovery of a building affects community resilience given the interdependencies between a building and its supporting lifeline infrastructure systems with in a community. It is important to map the interdependencies of infrastructure systems that provide services to a building when considering functional recovery of a building. Hence, frameworks for modelling and evaluating functional recovery of buildings also need to consider the interdependencies and interactions of different critical infrastructure systems beyond the building footprint. EERI (2019) also adovated that the design of functional recovery at the community level needs to consider all physical systems and any local cultural and religion institutes such as community churches. Cardoni et al. (2020) further added that the interdependencies among these systems could generate cascading failures and amplification effects, impacting on the engineering solutions to building restoration .

## 4.5 Ability to relocate functions and/or feed through alternatives

According to (Comerio, M. C., 2006; Comerio, Mary C. & Blecher, 2010), the possibility for a system to move and maintain its operations and services from the damaged building to another safe location would affect the timeframe of functional recovery for the building. This is particularly applicable to the lifeline infrastructure systems in the community or to an organisations with operational facilities that are concentrated in a high earthquake risk region (Comerio, 2006). The possibility for a system to be fed through alternative solutions during the restoration of the original damaged system has been defined as its redundancy (Bruneau et al., 2003).

## 4.6 Availability of resources

The availability of the reuqired repair materials influences heavily on the overall recovery time (Mishra, Fuloria, & Bisht, 2012; Terzic et al., 2021). Sufficient materials and tools around the affected region will aid the restoration of damaged buildings (Mishra et al., 2012). Restoration of buildings in a disaster-affected area also generates tremendous demand from human resources such as engineers, labourers, and management personnel (Rouhanizadeh, Kermanshachi, & Nipa, 2019). In addition, the ability of building owners and/or operators to secure funding for repairs also affects the time for resource mobilisation and decision-making prior to the start of repair (Wang & van de Lindt, 2021).

## 4.7 Resource allocation and repair scheduling method

In addition to the availability of resources the allocation and distribution of these resources also play an important role in the functional recovery process at the community level. Lack of a proper resource allocation plan could lead to mobilisation delays at the community or city level, even when the total resources available in the community is sufficient for recovery (Mieler et al., 2018). Optimisation tools such as the continuous Markov chain process can be utilised to estimate the resource distribution across different lifeline facilities dynamically (Hassan & Mahmoud, 2019).

## 4.8 Organisational networks and organisational capacity

After the 2010-2011 Canterbury earthquakes, the local businesses and organisations faced challenges which affected the recovery of their services due to damage to buildings and business premises (Stevenson et al., 2011). Therefore, organisational networks had notably supported the local businesses in their short-term response and recovery activities (Stevenson et al., 2014). Organisations can use these networks to address the issues in workforce redistribution and resources accessibility for early stage of recovery.

## 4.9 Social and community preparedness

Earthquake preparedness across social disciplines and industries has a major implication on the post-earthquake reactions and decision-making of the local communities (references). Seismic preparedness at the community level should consider technical, economic, social, and psychological aspects which affect the entire post-earthquake recovery process (Kirschenbaum, Rapaport, & Canetti, 2017). Providing local communities with accurate and continuous information and knowledge about hazards and risks can reduce not just the chances of human injury and property damage, but also the delay time for restoration and recovery as the consequence of social panic and lack of pre-earthquake planning (Kirschenbaum, Rapaport, & Canetti, 2017). In addition, insufficient Māori representations were found in planning for earthquake response and recovery after the 2010-2011

Canterbury earthquakes (Kenney et al., 2015). Lack of consultation with iwi and government agencies lead to less integrated decision making process for disaster recovery (references)).

### 4.10 Roles of governmental agencies

Government agencies play an important role in facilitating functional recovery and supporting overall resilience at the city and state level (EERI, 2019). Buildings and infrastructure systems need to be funded, designed, and regulated in different ways depending on recovery requirements.EERI advocated that the jurisdictions from the Federal or State agencies should identify the common recovery goals for their local buildings and facility systems to take the obligation of providing and upgrading public infrastructure. This can be done by clarifying these in local hazard mitigation plans or any relevant legislative actions. Additionally, more transparent public policies with precise codes and standards need to be established by the central government. Communities and owners of buildings can then be more intentional and explicit on the post-earthquake repair time required to restore to the desired level of functionality (EERI, 2019).

### 4.11 Multi-organisational communication and collaboration

The timeframes of functional recovery of buildings rely on the communication and collaborations of governmental agencies, organisations and communties. Improvement is still required to remove barriers to information exchanges and post-earthquake data sharing between multiple organisations involved in the recovery process (Blake et al., 2019). Clarification of organisational boundaries and the role of coordinators as the single point of contact need to be enhanced for better inter-organisational collaboration during the post-earthquake recovery process of infrastructure systems (Tagliacozzo, 2018).

## 5 FUNCTIONAL RECOVERY IN THE NEW ZEALAND CONTEXT

### 5.1 Functional recovery of lifeline facilities

The 2011 Christchurch earthquake caused signficant disruptions to lifeline utilities. Most damages resulted from extensive liquefaction in the central region of Christchurch City where concentrated lifeline facilities and multi-storey buildings were located (Giovinazzi et al., 2011). A good level of coordination and communication across lifelines facilities and government agencies can effectively limit interdependence issues. Mutual aid agreements and contingency measures in place can help lifelines facilities to prepare materials and technical experts for post-disaster repair in advance and respond to the reduced functionality of networks rapidly (Bellagamba et al., 2019; Giovinazzi et al., 2011; Liu et al., 2014) (Giovinazzi et al., 2011).

### 5.2 Functional recovery of multi-storey buildings

The resilience of multi-storey buildings is vital to ensure effective recovery after severe earthquake events. The 2010-2011 Canterbury earthquakes resulted in significant damage to business continuity in the downtown districts of Christchurch with high-rise buildings clustered together. approximately 150 “significant” buildings (generally commercial and multi-unit residential buildings over five storeys in the CBD) had been demolished, representing about 65 % of the significant buildings in the CBD and immediately surrounding neighbourhoods (Marquis et al., 2017). A large proportion of Christchurch’s central business district (CBD) fell into the post-earthquake red zone and more than 60% of the businesses in CBD were displaced after the 2011 earthquake (Canterbury Earthquakes Royal Commission, 2012). Study has shown that high-rise buildings commonly sustained heavier damage compared with low-rise to mid-rise buildings built with the same structure materials (Fikri et al., 2019).

## 6 DISCUSSION

The introduction of functional recovery in New Zealand can benefit decision making of restoring damaged buildings that have residual capacity following an earthquake event. It provides a new perspective of post-earthquake building restoration as a process of recovering the loss in building functionality. As such, it is essential to have an improved understanding of the factors that affecting the restoration process of a building. The cost and timeframe for functional recovery can then be estimated based on appropriate methodologies considering the major factors affecting the recovery of buildings. Such an understanding can better inform  building owners and other stakeholders on the details of technical and financial requirements for building restoration. The owners can also  make informed repair decisions based on the availability of technical, organisational, social and economic resources.

Moreover, research in functional recovery is aimed to inform changes needed to engineering practices and policies when considering the whole-life cycle functionality of a building. When considiering functional recovery in the design stage of a building,  and expected downtime, it can help building owners and insurance companies to better assess the risks and insurance coverage. Building owners and engineers are also able to develop a response and recovery plan for a building if an earthquake occurswith unique functionality requirements restored.

Recent earthquakes in New Zealand have caused social and economic damages to local communities. On the other hand, these earthquakes also provided valuable experience and lessons on functional recovery and highlighted the need for further improvement on the post-earthquake response and recovery strategies in New Zealand. As found by the critical review of previous studies, scholars around the world have started to notice the significant impact of factors beyond the physical damages on the functional recovery timeframes. The functional recovery of buildings is a complex process requiring the earthquake-affected region to be supported by sufficient technical, organisational, social and economic capacities. In order to improve the effectiveness and rapidity of post-earthquake recovery in New Zealand, several important knowledge gaps and areas of future research need to be addressed.

## 7 CONCLUSIONS

From the results of the critical review, we summarised the factors influencing the restoration of post-earthquake functionality into four categories, namely, 1) seismic resilience of the building itself, 2) resource availability for building repairs, 3) social and organisational preparedness and 4) governance. And then we discussed on the implications of functional recovery in the New Zealand engineering and building context.

The authors highlighted the impacts of the economic, social and organisational capacity of the communities on the functional recovery of buildings in New Zealand. The introduction of functional recovery notion and methodology will not only influence the decision making of restoring damaged buildings that have residual capacity after an earthquake. It can also inform the changes needed in engineering design practice and policy with whole-life cycle functionality taken into consideration. The importance of functional recovery needs to be understood and reflected in practices at all stages including design and construction, maintaining and monitoring, and the post-earthquake inspection and assessment.

## ACKNOWLEDGMENTS

This project was (partially) supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre.This is QuakeCoRE publication number 0758. The authors would like to thank the Doctoral Scholarship from QuakeCoRE Inter-disciplinary Programme 1. Without the funding support from QuakeCoRE, this research would not have been possible.

## REFERENCES

Alam, M. S., Sajjad, M. R., Yasir, Z., & Haque, F. M. M. (2013). A statistical study on structural characteristics of RC building stock of Dhaka city for seismic loss assessment application doi:10.4028/www.scientific.net/AMM.330.884

Almufti, I., & Willford, M. (2013). REDiTM Rating System: Resilience-Based Earthquake Design Initiative for the Next Generation of Buildings Arup.

Balaei, B., Noy, I., Wilkinson, S., & Potangaroa, R. (2021). Economic factors affecting water supply resilience to disasters. Socio-Economic Planning Sciences, 76 doi:10.1016/j.seps.2020.100961

Bellagamba, X., Bradley, B. A., Wotherspoon, L. M., & Lagrava, W. D. (2019). A decision-support algorithm for post-earthquake water services recovery and its application to the 22 February 2011 M (sub w) 6.2 Christchurch earthquake. Earthquake Spectra, 35(3), 1397-1420. doi:10.1193/052218EQS119M

Blake, D. M., Stevenson, J., Wotherspoon, L., Ivory, V., & Trotter, M. (2019). The role of data and information exchanges in transport system disaster recovery: A New Zealand case study. International Journal of Disaster Risk Reduction, 39 doi:10.1016/j.ijdrr.2019.101124

Bonowitz, D. (2011). Resilience criteria for seismic evaluation of existing buildings. San Francisco, CA:

Botha, P. S., & Scheepbouwer, E. (2015). Relationship between early contractor involvement and financial performance in the rebuilding of infrastructure in Christchurch, New Zealand doi:10.3141/2504-08

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., . . . Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra, 19(4), 733-752. doi:10.1193/1.1623497

Burton, H. V., Deierlein, G., Lallemant, D., & Lin, T. (2016). Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience. Journal of Structural Engineering (United States), 142(8) doi:10.1061/(ASCE)ST.1943-541X.0001321

Canterbury Earthquakes Royal Commission. (2012). Final report: Volumn 2 The performance of Christchurch CBD Buildings. ().

Cardoni, A., Cimellaro, G. P., Domaneschi, M., Sordo, S., & Mazza, A. (2020). Modeling the interdependency between buildings and the electrical distribution system for seismic resilience assessment. International Journal of Disaster Risk Reduction, 42 doi:10.1016/j.ijdrr.2019.101315

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. Engineering Structures, 32(11), 3639-3649. doi:10.1016/j.engstruct.2010.08.008

Comerio, M. C. (2006). Estimating downtime in loss modeling. Earthquake Spectra, 22(2), 349-365. doi:10.1193/1.2191017

Cretney, R. M. (2016). Local responses to disaster: The value of community led post disaster response action in a resilience framework. Disaster Prevention and Management, 25(1), 27-40. doi:10.1108/DPM-02-2015-0043

Earthquake Engineering Research Institute. (2019). Functional Recovery: A Conceptual Framework with Policy Options. Oakland, California: Earthquake Engineering Research Institute.

Earthquake Engineering Research Institute, (EERI) (Producer), & Earthquake Engineering Research Institute (Director). (2020). Functional Recovery: What it Means to Design for Community Resilience. [Video/DVD]

FEMA. (2001). FEMA P-58, Development of Next Generation Performance-Based Seismic Design Procedures for New and Existing Buildings. Retrieved from https://femap58.atcouncil.org/

FEMA. (2021). Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time FEMA.

Fikri, R., Dizhur, D., Walsh, K., & Ingham, J. (2019). Seismic performance of Reinforced Concrete Frame with Masonry Infill buildings in the 2010/2011 Canterbury, New Zealand earthquakes. Bulletin of Earthquake Engineering, 17(2), 737-757. doi:10.1007/s10518-018-0476-8

Giovinazzi, S., Wilson, T., Davis, C., Bristow, D., Gallagher, M., Schofield, A., . . . Tang, A. (2011). Lifelines performance and management following the 22 February 2011 Christchurch earthquake, New Zealand: Highlights of resilience. Bulletin of the New Zealand Society for Earthquake Engineering, 44(4), 402-417. doi:10.5459/bnzsee.44.4.402-417

Hassan, E. M., & Mahmoud, H. (2019). Full functionality and recovery assessment framework for a hospital subjected to a scenario earthquake event. Engineering Structures, 188, 165-177. doi:10.1016/j.engstruct.2019.03.008

He, L., Dominey-Howes, D., Aitchison, J. C., Lau, A., & Conradson, D. (2021). How do post-disaster policies influence household-level recovery? A case study of the 2010-11 Canterbury earthquake sequence, New Zealand. International Journal of Disaster Risk Reduction, 60 doi:10.1016/j.ijdrr.2021.102274

Johnson, G. S., Sheppard, R. E., Quilici, M. D., & Scawthorn, C. R. (1999). Seismic reliability assessment of critical
facilities: A handbook, supporting documentation, and model
code provisions.

Kenney, C. M., Phibbs, S. R., Paton, D., Reid, J., & Johnston, D. M. (2015). Community-led disaster risk management: A māori response to Ōtautahi (Christchurch) earthquakes. Australasian Journal of Disaster and Trauma Studies, 19, 9-20. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84929247376&partnerID=40&md5=548ff630c5245ca7583256b11616c1fc

Kinugasa, H., & Mukai, T. (2019). Damage evaluation index from the viewpoint of post-seismic functional recovery. Journal of Structural and Construction Engineering, 84(757), 425-435. doi:10.3130/aijs.84.425

Kirschenbaum, A. A., Rapaport, C., & Canetti, D. (2017). The impact of information sources on earthquake preparedness. International Journal of Disaster Risk Reduction, 21, 99-109. doi:10.1016/j.ijdrr.2016.10.018

Liu, M., Giovinazzi, S., MacGeorge, R., & Beukman, P. (2014). (2014). Wastewater network restoration following the canterbury NZ earthquake sequence: Turning post-earthquake recovery into resilience enhancement. Paper presented at the 160-167. doi:10.1061/9780784413234.021

Macaskill, K., & Guthrie, P. (2018). (2018). Funding mechanisms for disaster recovery: Can we afford to build back better? Paper presented at the , 212 451-458. doi:10.1016/j.proeng.2018.01.058

Mamula-Seadon, L., & McLean, I. (2015). Response and early recovery following 4 September 2010 and 22 February 2011 Canterbury earthquakes: Societal resilience and the role of governance. International Journal of Disaster Risk Reduction, 14, 82-95. doi:10.1016/j.ijdrr.2015.01.005

Marquis, F., Kim, J. J., Elwood, K. J., & Chang, S. E. (2017). Understanding post-earthquake decisions on multi-storey concrete buildings in Christchurch, New Zealand. Bulletin of Earthquake Engineering, 15(2), 731-758. doi:10.1007/s10518-015-9772-8

Mieler, M. W., & Mitrani-Reiser, J. (2018). Review of the State of the Art in Assessing Earthquake-Induced Loss of Functionality in Buildings. Journal of Structural Engineering (United States), 144(3) doi:10.1061/(ASCE)ST.1943-541X.0001959

Mieler, M., Paul, N., Almufti, I., & Lee, J. (2018). (2018). Predicting earthquake-induced downtime in buildings: An overview of the state of the art. Paper presented at the , 8 4778-4782. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85085585669&partnerID=40&md5=f01a94721abc7a003a3ee87a3167d8f2

Mishra, V., Fuloria, S., & Bisht, S. S. (2012). Enhancing disaster management by mapping disaster proneness and preparedness. Disasters, 36(3), 382-397. Retrieved from https://ezproxy.auckland.ac.nz/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=76574950&site=ehost-live&scope=site

Nguyen, C. N., & Noy, I. (2021). Measuring the impact of insurance on urban earthquake recovery using nightlights. Journal of Economic Geography, 20(3), 857-877. doi:10.1093/JEG/LBZ033

Rivera-Muñoz, G., & Howden-Chapman, P. (2020). Structural Adjustment and Community Resilience: The Case of Postdisaster Housing Recovery After the Canterbury Earthquakes of 2010 and 2011. Health Education and Behavior, 47(6), 805-815. doi:10.1177/1090198120936611

Rouhanizadeh, B., Kermanshachi, S., & Nipa, T. J. (2019). (2019). Identification, Categorization, and Weighting of Barriers to Timely Post-Disaster Recovery Process. Paper presented at the ASCE International Conference on Computing in Civil Engineering 2019: Smart Cities, Sustainability, and Resilience, i3CE 2019, June 17, 2019 - June 19, 20, 41-49. doi:10.1061/9780784482445.006

Stevenson, J. R., Chang-Richards, Y., Conradson, D., Wilkinson, S., Vargo, J., Seville, E., & Brunsdon, D. (2014). Organizational networks and recovery following the Canterbury earthquakes. Earthquake Spectra, 30(1), 555-575. doi:10.1193/022013EQS041MR

Stevenson, J. R., Kachali, H., Whitman, Z., Seville, E., Vargo, J., & Wilson, T. (2011). Preliminary observations of the impacts the 22 February Christchurch earthquake had on organisations and the economy: A report from the field (22 February - 22 March 2011). Bulletin of the New Zealand Society for Earthquake Engineering, 44(2), 65-76. doi:10.5459/bnzsee.44.2.65-76

Tagliacozzo, S. (2018). Government Agency Communication during Postdisaster Reconstruction: Insights from the Christchurch Earthquakes Recovery. Natural Hazards Review, 19(2) doi:10.1061/(ASCE)NH.1527-6996.0000283

Terzic, V., Villanueva, P. K., Saldana, D., & Yoo, D. Y. (2021). Framework for modelling post-earthquake functional recovery of buildings. Engineering Structures, 246 doi:10.1016/j.engstruct.2021.113074

Terzic, V., Yoo, D. Y., & Aryan, A. H.Repair Time Model for Buildings Considering the Earthquake Hazard. 2016 SEAOC Convention Proceedings, 562-571.

Vallance, S. (2011). Early disaster recovery: A guide for communities. Australasian Journal of Disaster and Trauma Studies, 2011(2), 19-25. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-84867624972&partnerID=40&md5=3c4a17a6fed714e17bdcf4e5664f702d

Wang, W. L., & van de Lindt, J. W. (2021). Quantitative modeling of residential building disaster recovery and effects of pre- and post-event policies. International Journal of Disaster Risk Reduction, 59 doi:10.1016/j.ijdrr.2021.102259

Xiong, C., Huang, J., & Lu, X. (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(4), 322-341. doi:10.1111/mice.12496