

BUILDING SEISMIC RESILIENCE FOR NEW ZEALAND - PAST, NOW, AND FUTURE

Liyan Li¹, Alice Chang-Richards², Megan Boston³, Ken Elwood², & Carlos Molina Hutt⁴

¹ University of Auckland, Auckland, New Zealand, yil631@aucklanduni.ac.nz

² University of Auckland, Auckland, New Zealand

³ University of Waikato, Hamilton, New Zealand

⁴ The University of British Columbia, Vancouver, BC, Canada

Abstract: *The 2010/2011 Canterbury earthquakes exposed deficiencies in building performance, particularly in terms of interrupted functionality, extensive downtime, and uneconomical repairability. Amid the increasingly acknowledged emphasis on improving building resilience, the post-earthquake recovery has witnessed the emergence of a series of low-damage designs for retrofitted and newly constructed buildings, alongside a growing recognition of a functionality-centric approach to building codes. By collecting data from a joint US-New Zealand study tour, this research identified the resilience practices that had taken place after the 2010/11 Canterbury earthquakes to enhance building seismic performance in New Zealand. A number of low-damage design solutions have been observed. However, their adoption has also been hindered by factors such as a lack of finance, evidence-based information, skills and expertise, and community engagement, compounded by complexities of legislation requirements. To foster functional recovery-oriented building performance, there needs to be a systemic approach, including 1) sufficient performance validation of more advanced building designs, 2) revisions to building codes to provide an enabling regulatory environment, 3) widespread public education and communication in building risk mitigation, and 4) accessible training programs provided by engineering professional organisations such as Engineering New Zealand (ENZ), New Zealand Society of Earthquake Engineering (NZSEE), and Structural Engineering Society New Zealand (SESOC) for engineers on low-damage design concepts and risk-targeted design for maintaining functionality.*

1. Introduction

The 2010/2011 Canterbury earthquake sequence resulted in significant consequences, including the loss of 185 lives, the demolition of nearly 1,600 buildings in the Christchurch central business area (CBD), the substantial financial losses of almost NZD 40 billion (the equivalent of almost 20% of New Zealand's gross domestic product (GDP)) (ICNZ, 2023), and the inaccessibility of CBD for over two years (McGuigan *et al.*, 2017). Prior to the February 2011 earthquake, Christchurch was believed only to have moderate seismic exposure (NZSEE, 2011). When the M6.2 February 2011 event occurred, the severity of shaking and scale of building damage came as a surprise. Response spectra for a number of recorded sites exceeded 500-year design levels, in some cases by a substantial margin (Christchurch City Council, 2013). With such a significant earthquake level, a majority of the older unreinforced masonry (URM) buildings and stone churches have suffered severe damage or partial collapse (Comerio *et al.*, 2011; Gonzalez *et al.*, 2021; MBIE, 2012). Two modern buildings (the Pyne Gould Corporation (PGC) building (designed in 1963) and the Canterbury Television (CTV) building (designed in 1986)) collapsed catastrophically (Kaiser *et al.*, 2012), which caused

the primary fatalities. Apart from those two buildings (and the exceptions of the performance of stairs, attachment of panels, and some nonstructural elements), other modern buildings met the goal of life safety that underpins New Zealand’s current building regulatory regime. In most cases, however, this was accompanied by significant structural and nonstructural damage (Canterbury Earthquake Royal Commission, 2012). As such, a complete rebuild of the city centre has been undertaken. With a particular focus on seismic-resilient buildings (Skidmore *et al.*, 2022), different seismic resilient technologies (e.g., low-damage designs) were employed in both retrofitted and newly constructed buildings in Christchurch to enhance building seismic performance (Bruneau *et al.*, 2017; Li *et al.*, 2023b).

To enhance building seismic performance, it is crucial to consider what performance levels should be targeted for more resilient buildings. Specifically, the current seismic design philosophy is still performance-based and sets out the minimum performance requirements for buildings (Uma *et al.*, 2013). There are four commonly considered performance levels, including collapse, life-safety, operational, and fully operational. Figure 1 presents the relationship between earthquake intensity and different performance levels (Buchanan *et al.*, 2011). Notably, the New Zealand Building Code still addresses life safety under rare events and serviceability under frequent events as minimum requirements to address tolerable levels of safety and health concerns of occupants (Buchanan *et al.*, 2011). However, as evidenced by the 2010/2011 Canterbury earthquakes, those code-compliant buildings cannot provide continued functionality, reduced damage, and economical repairs (Canterbury Earthquake Royal Commission, 2012; Li *et al.*, 2023a; Molina Hutt *et al.*, 2022). Broader communities expected buildings to be resilient enough to maintain their functions (Li *et al.*, 2023b; Molina Hutt *et al.*, 2022) and to gracefully degrade when necessary (Allenby *et al.*, 2005). In alignment with such expectations, it is suggested that all buildings should remain at least operational (see Figure 1) regardless of the building Importance Level (Buchanan *et al.*, 2011; Campbell, 2018; Canterbury Earthquake Royal Commission, 2012), which also refers to functional recovery level from a functionality-oriented perspective. Buildings designed with functional recovery-based objectives shall be able to provide basic intended functions within an acceptable recovery timeframe (EERI, 2019; Sattar, 2021).

Earthquake design levels	Earthquake performance levels			
	Fully operational	Operational	Life-safe	Near collapse
	REPAIRABLE		NON-REPAIRABLE	
Frequent (40 years)	Unacceptable	Unacceptable	Unacceptable	Unacceptable
Occasional (100 years)	Marginal	Unacceptable	Unacceptable	Unacceptable
Rare (550 years)	Unacceptable	Unacceptable	Unacceptable	Unacceptable
Very rare (2500 years)	Unacceptable	Unacceptable	Unacceptable	Unacceptable

Figure 1 Suggested performance-objective matrix (Source: Buchanan *et al.* (2011))

Revising building codes to meet functional recovery objectives is a worldwide ongoing endeavour. The ultimate goal of functional recovery design objectives is to reduce potential downtimes of critical infrastructure assets and services on which communities rely, thus improving community resilience to future hazards. It is a long-standing need identified across engineering, resilience, and risk mitigation fields and is also recognised as a national priority in the NIST-FEMA report (FEMA P-2090 / NIST SP1254) (Sattar, 2021). More recently, in the United States, the Building Seismic Safety Council (BSSC), operating through the Provisions Update Committee (PUC), has established a Functionality Recovery Task Committee (FRTC) to specifically develop technical proposals and other resources regarding the design of new buildings to meet post-earthquake functional recovery performance objectives within the context of the 2026 NEHRP Provisions (Blowes *et al.*, 2023). These technical proposals and other resources will also serve as source material for proposals for possible adoption and use in other codes and standards for new buildings, such as *ASCE/SEI 7 Minimum Design Loads and Associated Criteria for Buildings and Other Structures* and the *International Building Code*. In addition, with the recognition of the inadequacy of code-compliant buildings after the 2010/2011 Canterbury

earthquakes in New Zealand, the Ministry of Business, Innovation & Employment (MBIE) has established the Seismic Work Programme to ensure the building system adapts to new knowledge around building performance. This endeavour aims to lay a substantial groundwork for Building Performance, which is responsible for managing New Zealand's central regulatory system for building and making legal changes to Building Codes. Notably, in July 2022, MBIE released the new seismic risk guidance to help people make informed decisions about buildings with a low seismic rating (Building Performance, 2022). Also, in October 2022, the updated National Seismic Hazard Model (NSHM) was released, which provides basic seismic parameters for the design of structures to meet societal performance expectations and inform seismic risk assessment (GNS Science, 2022). Moreover, a spectrum of research has also been initiated to promote functional recovery and develop solutions to maintain and restore building function following a large earthquake. For example, the QuakeCoRE has established a series of interdisciplinary research programs to identify time-to-functionality targets and repairable building solutions, thus providing the underlying science to support the development of the world's first functional recovery-based seismic design standard.

Low-damage design is a new approach to building earthquake-resilient structures. It not only focuses on preserving life in a major event but also on preserving the primary structure of the building, leaving it usable or easily repairable following an earthquake. The primary objective of low damage designs is to design new forms of lateral load-resisting structures where damage is either suppressed or limited to readily replaceable elements (Canterbury Earthquake Royal Commission, 2012; SCNZ, 2023). It can give greater building resilience by providing damage reduction in the primary structural systems, with the potential to reduce damage to nonstructural components and building content (Bianchi *et al.*, 2020; Campbell, 2018). An effective low damage design should have the following properties: damage mitigation effectiveness, reparability, self-centring ability, limited nonstructural damage, durability, and affordability (Hare *et al.*, 2012). With these design requirements, low damage designs can be deemed effective and potential solutions to provide more resilient buildings with reduced risks regarding damage exposure, financial losses, and extensive downtime that align with functional recovery objectives. However, more solid evidence should be provided by assessing the performance of those designs concerning building functionality or functional recovery objectives (Joyner *et al.*, 2021).

In light of the need to build more resilient buildings, it is imperative to derive the policies that should be in place to facilitate the adoption of more advanced designs based on the lessons learned from past resilience practices. Toward this end, an extensive joint US-Aotearoa (New Zealand) study tour was conducted to Wellington, Kaikōura, and Christchurch in April 2023. This study tour encompassed a diverse range of research activities, including technical site visits, field trips, and technical presentations and workshops. By gathering firsthand empirical data and integrating different perspectives from diverse professionals, this research aspires to 1) offer a comprehensive overview of resilience practices implemented in response to the 2010/2011 Canterbury earthquake sequences, 2) identify various factors influencing the acceptance and adoption of low-damage designs in Christchurch, and 3) elicit practical policy recommendations to facilitate the advancement of more resilient designs in New Zealand.

2. Literature Review

The concept of resilience has been broadly utilised in different disciplines, ranging from environment, engineering, psychology, sociology, and economics. The resilience of a structure is commonly referred to as “the ability to withstand, adapt to, and recover from disasters” (Asprone *et al.*, 2014). Bruneau *et al.* (2003) further identified four attributes of resilience, including robustness, redundancy, resourcefulness, and rapidity. When designing a building for earthquake resistance, robustness is a primary consideration to provide the structure with the ability to maintain its structural integrity, functionality, and safety even in the presence of unexpected or extreme events. For instance, the New Zealand Building Code clause B1 *structure* has provided clear clauses that define the primary objective of structures to maintain stability and prevent structural failure (New Zealand Legislation, 2023). Therefore, most of these code-compliant buildings perform well in preventing building collapse and the loss of life. However, under such building design philosophy, some will need to be demolished because repairs are not economically viable, as evidenced by the high proportion of demolished buildings in the aftermath of the 2010/2011 Canterbury earthquakes (Gates, 2015).

Moreover, redundancy refers to the extent to which alternative elements, systems, or other measures exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation

or loss of functionality, and rapidity is the capacity to meet priorities and achieve goals promptly in order to contain losses, recover functionality and avoid future disruption (Bruneau *et al.*, 2003; Cimellaro *et al.*, 2010). Redundancy and rapidity emphasise the ability of the structure to provide continued functionality and fast recovery, which have not been comprehensively tackled through explicit design considerations as the current seismic design philosophy still focuses on preserving life safety and preventing significant structural failures. Improving the strength and stiffness of the structure further, such as increasing the design level, is a prevalent design practice to enhance building performance. The recognition of the continued functionality and acceptable recovery time through an additional emphasis on redundancy and rapidity demonstrate a pursuit of building performance beyond traditional life safety and collapse prevention objectives. This recognition emphasises recovery and adaptation, which reflects a paradigm shift that places building functionality at the centre of the design (Cimellaro *et al.*, 2021; Cimellaro *et al.*, 2016; Joyner *et al.*, 2021). In this case, the expression of resilience can be assessed by the level of building functionality (Mieler *et al.*, 2018; Terzic *et al.*, 2021; Yavari *et al.*, 2010). Using functionality as a metric for building resilience is an essential aspect of setting resilience as a design objective.

A number of design strategies can improve the seismic resilience of structures. Most practices have targeted resilience through a risk reduction approach. For example, two primary limit states are used by AS/NZS 1170 structural design actions- the serviceability limit state (SLS) and the ultimate limit state (ULS) to ensure a low probability of building collapse across all rare events and therefore the risk to human life is at an acceptable level (Standards New Zealand, 2004). Moreover, US building codes aim at achieving a target collapse probability of 1% in 50-years—with a conditional 10% collapse probability for an approximate 2475-year return period event to ensure acceptable seismic resilience of buildings (ASCE, 2010). Nevertheless, a notable limitation of this risk reduction-oriented approach is that a significant investment in robustness yields diminishing returns. With this idea in mind, another avenue to building resilience is through a recovery-based approach. In this context, rapidity has been recognised as a hallmark of resilient buildings, where downtime to recover building functionality should be in an acceptable timeframe (EERI, 2019; Li *et al.*, 2023a). Failure to recover fast can result in enduring disruptions to the community (Chang *et al.*, 2014). There are lots of research efforts focused on developing reliable frameworks to predict recovery time at the individual building level (Cook *et al.*, 2022; Molina Hutt *et al.*, 2022), where downtime due to impeding factors and repair time have been explicitly explored and evaluated. Meanwhile, external factors extending beyond the building structure, such as resource availability and the serviceability of surrounding infrastructure, have also been acknowledged as critical considerations that should be thoroughly addressed when pursuing community resilience at a broader scale (Alisjahbana, 2022; Li *et al.*, 2023b). These endeavours provide the essential and valuable knowledge to incorporate recovery-based objectives in future building designs to improve the seismic resilience of structures.

In addition, the interim improvement of building resilience is possible at the technical dimension levels. Higher-performance building technology is developed to facilitate recovery by providing qualities of limited damage and graceful repairability. Design for graceful repairability means that damage is allowed, but repair of the damage should be either easy or have fewer disruptions to critical building functions (Allenby *et al.*, 2005). In contrast, design for buildings with controlled damage involves techniques where the structure is designed to be flexible and ductile to absorb and dissipate seismic forces. Currently, low-damage designs (e.g., dampers) have drawn worldwide attention as a promising solution to providing more resilient buildings with controlled building performance (Bianchi *et al.*, 2020; Campbell, 2018; SCNZ, 2023; Skidmore *et al.*, 2022). However, the performance of those more advanced designs should be further validated and tested to ensure the expected building performance outcomes during the lifetime. In particular, low damage building technology is mainly developed to minimise structural damage and is not directly concerned with nonstructural components. However, it should be noted that the financial losses resulting from non-structural damage can be pretty significant, necessitating the demolition of a structure in the aftermath of the 2010/2011 Canterbury earthquake sequence (Li *et al.*, 2023b; Lucas, 2016). The seismic performance of a resilient building depends on the performance of both structural and nonstructural components (Bruneau *et al.*, 2007). Therefore, more detailed consideration for nonstructural components is imperative within the design philosophy of low damage designs.

3. Research Methodology

This research aspires to identify resilience strategies in New Zealand after the 2010/2011 Canterbury earthquakes and derive pragmatic policies for having more resilient buildings. Toward this end, this study employed a methodology characterised by three distinct steps, as depicted in Figure 2. A US-Aotearoa (New Zealand) study tour was undertaken in Wellington, Kaikōura, and Christchurch from April 22nd to April 29th 2023. Specifically, this study tour encompassed a multitude of research activities, including technical site visits, field trips, and technical presentations and workshops. These activities were carefully designed to provide invaluable insights into the historical backdrop of restoration practices in New Zealand following the 2010/2011 Canterbury earthquake sequence. The presentations and technical sessions during this tour delved into diverse subjects, including (a) past practices for enhancing resilience employing a variety of protective devices in Wellington and Christchurch, (b) the reconstruction efforts in Christchurch, the challenges encountered, and the lessons learned from prior practices, and (c) the strategies for improving building and community resilience against future disruptive events. In order to incorporate multiple perspectives from various stakeholders, this study tour intentionally involved a diverse cohort of professionals, ranging from professors and engineers to contractors and PhD candidates. Based on on-site observations and data collected from interactive workshops and presentations, we have identified the critical barriers to improving building resilience in New Zealand. Several policy recommendations were elicited when looking into a recovery-based building performance regime in the future.

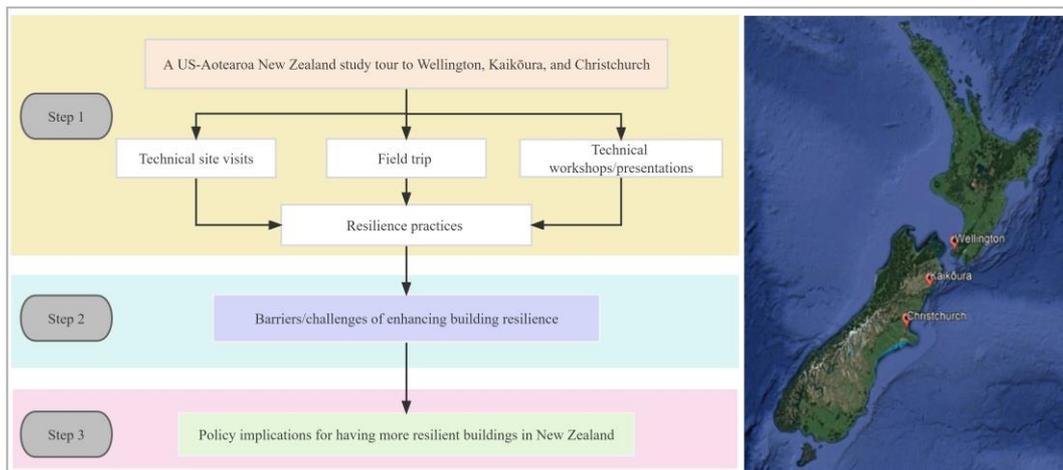


Figure 2. Methodology design

4. Results and Discussion

4.1. Resilience practice in New Zealand

The 2010/2011 Canterbury earthquakes highlighted the severe mismatch between the expectations of building owners and the reality of the seismic performance of buildings. Low damage designs have been widely adopted to achieve better building performance by reducing damage in the primary structural systems, with the potential to reduce damage to nonstructural components and building contents (Canterbury Earthquake Royal Commission, 2012). Through the field trip conducted to both Wellington and Christchurch, various structural systems and resilient techniques (e.g., base isolation and dissipative devices) can be readily identified in Christchurch CBD.

Base isolation is a passive structural control technique that separates the building from the ground, effectively preventing the direct transmission of earthquake ground motions into the structure, thus protecting the building's structural integrity. Prior to the devastating 2010/2011 Canterbury earthquakes, only one building (Christchurch Women's Hospital) utilised base isolation and expectedly did not suffer any damage during the earthquakes (Buchanan *et al.*, 2011). Twelve years since the February 2011 earthquake, Christchurch CBD now has a total of 16 buildings with base isolation installed. A number of newly constructed and retrofitted steel buildings also have base isolation bearings. One prominent example is the retrofitted Christchurch Art Gallery, as depicted in Figure 3. Its base isolation system was implemented by placing the underground portions of the

building on flexible bearings or isolators. These isolators are designed to absorb and dissipate seismic energy during an earthquake, thus reducing the transmission of ground motion to the structure and protecting the valuable artwork.



Figure 3. Christchurch Art Gallery: (a) Global view; (b) Base isolator in the underground

Furthermore, more advanced base isolation systems were also introduced in rebuilding Christchurch. For example, 151 Cambridge Terrace (see Figure 4) incorporated Triple Pendulum base isolation bearings, making it one of the most earthquake-resilient buildings in the country. Specifically, three pendulum components stack on top of each other to provide a wide range of flexibility and movement in response to ground shaking. This solution helps to dissipate seismic energy and minimise the transfer of damaging forces to the building.

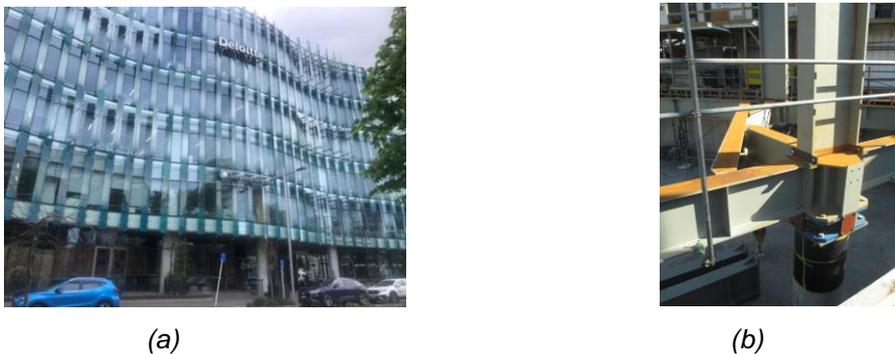


Figure 4. 151 Cambridge Terrace: (a) Global view; (b) Base isolator in the underground (Courtesy of Aurecon)

In addition, damping systems (e.g., viscous dampers) have been adopted to reduce the amplitude of vibrations and control the building's response to ground motions. By dissipating energy, dampers help protect the structure from excessive deformation and potential damage. Also, by reducing the magnitude of vibrations, damper devices improve the comfort and safety of occupants during an earthquake (Bruneau *et al.*, 2017). For example, Tūranga Library, which is a newly built library in the centre of Christchurch city (see Figure 5), used a dual seismic resisting system, primarily consisting of an integrated self-centring mechanism in the form of hybrid concrete shear walls that rock to isolate the building from peak earthquake accelerations. The large extrusion dampers are strategically bolted at critical points between the base walls and the foundation, which act as motion restraints to earthquake forces.

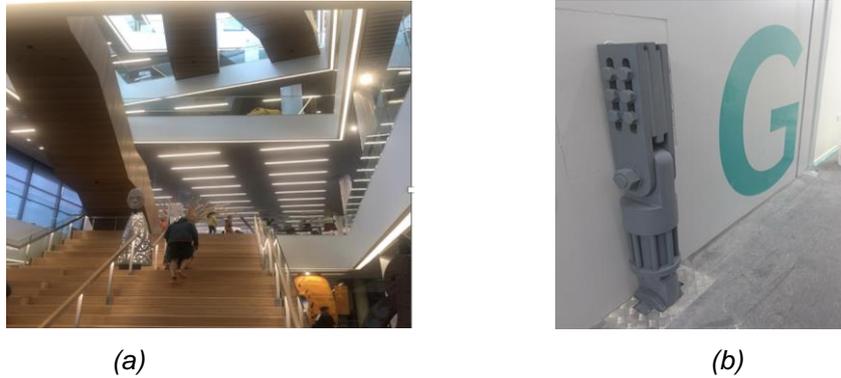


Figure 5. Tūranga Library: (a) Interior of the library; (b) Viscous dampers on ground level (Courtesy of Moata Tamaira, Reference: Tūranga-2018-09-06-DSC03669 Christchurch City Libraries)

Furthermore, steel buckling restrained braced (BRB) frames are also incorporated in the building repair and rebuilding efforts. BRB effectively provide strength and ductility to the structure, and its braces can prevent buckling and maintain their load-carrying capacity even under severe earthquake shaking. For example, the BRBs adopted by PwC Centre (see Figure 6) can yield the internal steel core in tension and compression with the outer steel casing, preventing the internal steel core from buckling. PwC building is designed to yield the piece of flat steel inside the brace, which absorbs the energy of an earthquake; the concrete case retains the plate and stops it from seriously deforming. The braces can be readily removed and replaced for ease of repairs.



Figure 6. PwC Centre: (a) Architecture view (Courtesy of Beca); (b) Close-up view of bracing (Courtesy of Steel Construction New Zealand)

Furthermore, rocking walls/frames were also broadly adopted during the reconstruction of Christchurch. Rocking walls/frames are designed to self-centre after an earthquake, restoring the structure to its original position. The rocking motion of the frames/walls reduces the lateral forces acting on the structure, leading to a lower risk of structural damage. For instance, the rocking frames used in 141 Cambridge Terrace are anchored at their base using sizable springs to restrict the initiation of rocking motion. Additionally, RC structures are still utilised in the rebuilding of Christchurch. RC structures can effectively resist the lateral forces and ground motion associated with earthquakes. The versatility of RC structures allows for flexible design solutions that meet specific requirements. RC elements can be moulded and shaped to accommodate various architectural styles, building configurations, and functional needs. The availability of concrete as a widely accessible material, coupled with the well-established construction techniques associated with RC structures, contributes to the efficient and timely completion of projects.

4.2. Barriers to enhancing building resilience

Lack of evidence-based performance information

Low-damage designs can reduce the demand on the structure or effectively control the response of the structural and nonstructural components, therefore reducing possible damage sustained by the structure. However, there is still a substantial dearth of empirical evidence-based information regarding the performance outcomes of structural and nonstructural components when using low-damage designs. Notably, while most low-damage designs primarily focus on structural performance, the exploration of nonstructural component performance remains inadequately examined. It is essential to highlight that numerous experimental and theoretical tests have been conducted to validate different performance aspects of low-damage designs. However, these experiments and tests are typically conducted within a controlled laboratory environment, involving certain assumptions and simulation conditions. The testing of various variables often takes place in an isolated manner, raising the possibility that the performance of structures utilising low-damage designs may differ when the structures are situated in a real-world environment with occupants present. With limited empirical evidence regarding the building performance of low damage designs during its lifespan, engineers cannot have the confidence to demonstrate that such low-damage designs can sufficiently meet the performance objectives of the building codes to suggest alternative solutions for clients.

Cost and financial constraints

Unlike other developed countries, New Zealand has a wide insurance penetration/coverage for commercial and residential buildings. After the 2010/2011 Canterbury earthquakes, approximately 80% of the losses were covered by insurance (Marquis *et al.*, 2017). Notably, the terms of insurance are generally for “reinstatement”, which means an insured structure will only be returned to “as new” condition. According to the New Zealand Insurance Council (Lucas, 2016), the insurance sector faces limitations in promoting the adoption of construction methods that surpass code requirements regarding seismic performance, such as low-damage construction or better design/construction of nonstructural elements. This is because New Zealand insurance holds only a marginal share of less than 0.1% in the global reinsurance market, and other international drivers control the conditions in New Zealand (Bruneau *et al.*, 2017). As such, designing low damage structures should be prudent, as insurance is unlikely to cover all expenses beyond the upper limit. Through the field trip to Wellington and Christchurch, it was found that the general notion of high perceived costs and lack of credibility and confidence among the public and engineers was a significant factor that hindered the implementation of low damage designs. In particular, though the low damage designs can prevent future significant financial losses, private building owners are more concerned about the cost of implementing such designs.

Complex legislation context

After the 2010/2011 Canterbury earthquakes, New Zealand standards did not generally change to encourage construction that is more resilient. There have been two critical regulatory changes, notably: (1) an increase in the seismic zone factor from 0.22 to 0.30 for Christchurch and its surrounding area, and (2) the serviceability level event shaking considered in design increased from 25% to 33% of the 500-year return period shaking for ordinary structures shortly after the earthquakes. However, it was reverted to 25% in late 2016. In this case, increasing the level of seismic design loading is still the primary course of action to improve building performance, as opposed to higher-performance building technology. In addition, according to the New Zealand Building Act (MBIE, 2004), low-damage technologies are not included in the Building Code as designated “acceptable solutions” or “verification methods”, and no specific New Zealand Standards are catering to them. In this case, though low damage designs can still be used by demonstrating that the performance requirements of the building code have been met, the consent process is inevitably more expensive than for buildings of conventional design, as this process relies not only on detailed building consent applications that demonstrate the robustness of the technology but also on a receptive and educated response from the individual building consent authority (Canterbury Earthquake Royal Commission, 2012).

Lack of skills and expertise

The implementation of low damage designs faces a significant hurdle in the form of a lack of skills and expertise. Adopting these innovative designs requires specialised knowledge and technical know-how that may not be readily available within the industry. Engineers, architects, and construction professionals often encounter difficulties in understanding the intricate details and complexities associated with low damage

design principles. Additionally, the training and educational programmes available to develop these skills are limited, further exacerbating the expertise gap. A lack of skills and knowledge of design has to a great extent slowed its implementation.

Limited community engagement and communication

Limited community engagement and communication are often observed in the adoption and implementation of low damage designs. Specifically, while building owners have acknowledged their general expectations concerning building performance in terms of continued building functionality and minimised downtime alongside life safety requirements, many of them are not fully informed about how these advanced designs can meet their expectations and what level of resilience these designs can offer for their assets, especially when conventional designs can also meet the basic performance requirements. The insufficient communication regarding building seismic performance and the potential benefits offered by these more advanced designs in comparison to conventional ones makes the community possess limited knowledge and understanding. This limitation affects their inclination to consider these advanced designs as alternatives when they are simultaneously presented with multiple design options.

4.3. Recommendations for policies for enhancing building resilience

Sufficient performance validation

Past resilience initiatives have indicated the effectiveness of low damage designs to enhance building performance. However, there is still a lack of empirical evidence-based information regarding their intended performance in terms of damage mitigation effectiveness, reparability, self-centre ability, nonstructural and content damage, durability, and affordability. Such information can be invaluable in communicating the potential benefits of those designs to various stakeholders. In this regard, extensive research, experiments, and tests are needed to authenticate the performance of these building designs and to tackle maintenance concerns throughout the building's lifespan. Importantly, with the recognition of shifting design focus from performance-based to functionality-based approaches, there is a need for a robust technical examination to ensure that low damage designs can achieve intended objectives to maintain functionality, enable rapid re-occupancy and support more resilient building design.

Recovery-based building codes

Revising building codes is a long-term commitment to aligning societal expectations with building performance. This endeavour necessitates a paradigm shift from a predominant emphasis on life safety toward an approach centred on recovery-based (functionality-based) objectives. In addition to life safety, other performance goals, including downtime and graceful reparability, should be explicitly included in building codes and considered in future building designs. In particular, specific performance requirements for structures with different Importance Levels under considered levels of seismic hazard risk need to be delineated within building codes. In addition, in light of the promising solutions through low damage designs to enhance building resilience, it would be beneficial to offer certain clarifications within building codes to facilitate the building consent process of these advanced building designs.

Indeed, there are ongoing endeavours in New Zealand that consistently facilitate initiatives for building code revision and the design of more resilient structures. For example, in August 2022, the technical societies published the *Earthquake Design for Uncertainty guidance* to provide sound design principles to reduce uncertainty in building performance (NZSEE *et al.*, 2022). As mentioned before, in October 2022, GNS Science released the updated NSHM, which establishes a robust foundation for determining seismic performance objectives and expectations of a range of buildings (GNS Science, 2022). Also, the SESOC, NZSEE, and the New Zealand Geotechnical Society (NZGS) have collaborated to publish an advisory document giving interim guidance to design professionals and their clients until any future updates are made to the New Zealand Building Code (SESOC *et al.*, 2022). While acknowledging that the latest science offered by NSHM can inform design requirements within the Building Code, it will take time for MBIE to consider how to incorporate NSHM results into the Building Code. Therefore, engineers should continue to use the design earthquake actions of NZS 1170.5:2004 (as cited by B1/VM1 on July 1 2017) to demonstrate that the design of structures complies with the minimum performance requirements in the Building Code.

Public education/communication

To facilitate the acceptance of resilient techniques, communities should possess an accurate understanding of the seismic performance of their buildings and the potential benefits in terms of building performance improvement through the utilisation of alternative resilient designs. Meanwhile, the misconceptions about the perceived higher costs associated with implementing these techniques should also be addressed. As such, ongoing educational initiatives within the broader community are necessary. A multifaceted approach can be employed, including (a) disseminating easily accessible and comprehensible educational materials (e.g., brochures); (b) cultivating transparent dialogue between engineers, academia, and the public through open communication channels, such as public forums, seminars, and workshops; (c) proactively involving educational institutions, local organisations, and media entities to integrate seismic resilience topics within curricula or coverage; and (d) enhancing community participation and public involvement in pertinent decision-making processes.

Training programmes for engineers

While design tools and technical solutions constitute fundamental prerequisites to creating more resilient buildings, the availability of qualified engineers is essential. Training programmes provided by professional engineering organisations such as Engineering New Zealand (ENZ), NZSEE, and SESOC should be available for engineers on low-damage design concepts and risk-targeted design for continuous functionality. By imparting specialised knowledge and advanced techniques, these programmes can equip engineers with the necessary skills to comprehend the intricate nuances of functional recovery-based designs. Through hands-on training and theoretical instruction, engineers can comprehensively understand design considerations, retrofitting methodologies, and innovative technologies pertinent to enhancing building resilience. Furthermore, such training programmes instil a culture of continuous learning and adaptation, enabling engineers to stay informed of the latest advancements in the field and to respond to evolving challenges swiftly.

5. Conclusions

In the aftermath of the devastating 2010/2011 Canterbury earthquakes, improving seismic resilience has been a focus in New Zealand. This study conducted a field trip to Wellington, Kaikōura, and Christchurch to investigate the resilience practices adopted. It was found that innovative low damage design solutions, including base isolation, damper, BRB frames, and rocking walls, have been utilised in Christchurch to enhance building resilience. However, although implementing those design solutions proved beneficial, their implementation and adoption are challenging in some cases due to a number of factors, including lack of reliable empirical performance information, financial constraints, intricate legislative contexts, limited expertise and skills, as well as inadequate community engagement and collaboration.

A set of policy recommendations was formulated to facilitate the acceptance and utilisation of low damage designs. Specifically, there remains a necessity for thorough performance validation supported by robust empirical evidence pertaining to low-damage designs. It is equally essential to revise building codes and the consenting process, establishing a conducive regulatory environment that normalises the selection of low-damage designs. Such revisions would also empower engineers to communicate with their clients confidently. Concurrently, continuous educational initiatives targeting broader communities should be implemented to ensure communities possess an accurate understanding of their building's performance and the potential benefits associated with the adoption of low damage designs. Given the technical intricacies of low-damage designs, accessible training programs tailored for engineers remain imperative to ensure the technical capacity to implement these resilient designs. It is hoped these policy options can strategically promote the understanding and acceptance of low damage designs in an integrated manner.

The findings revealed by this research are derived from an extensive empirical study tour, which is advantageous to gather firsthand observations and insights, offering a holistic perspective on past resilience practices. However, future research is still needed for more extensive field trips across various seismic risk regions of New Zealand, specifically comparing resilience practices across different jurisdictions that are at high seismic risk. Such reconnaissance for earthquake recovery and resilience efforts could yield valuable insights into where the gap in both research and practice lies between now and the future.

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