

## EERI Learning From Earthquakes Program Travel Study Report:

# Reconfiguring New Zealand's Built Environment After the 2010-2011 Canterbury Earthquake Sequence and the 2016 Mw 7.8 Kaikoura Earthquake

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#### 1 INTRODUCTION

Earthquake effects are felt most acutely at the local level, where the community grieves the loss of life and livelihoods while simultaneously trying to move forward and establish a new normal. However, communities that make it through such a harrowing event can offer both caution and hope to their neighbors worldwide. In May 2019, the Earthquake Engineering Research Institute organized a team of young professionals to learn from New Zealand's experience during and after the Canterbury Earthquakes in 2010-2011 and the Kaikoura Earthquake in 2016 through EERI's Learning from Earthquakes (LFE) Travel Study Program. By speaking with first responders, engineers involved in reconstruction, business owners, and government officials, and observing the state of recovery several years after the earthquakes, not simply the initial damage, the Travel Study participants identified exemplary aspects of New Zealand's recovery process, as well as challenges that warrant further consideration. This report focuses on the lessons learned with regards to the recovery of the built environment, concluding with observations on how these lessons could be applied to mitigate disaster risk and improve community resilience.

#### Earthquake Background

The moment magnitude ( $M_w$ ) 7.1 Darfield earthquake occurred on September 4th, 2010 at 4:35 am (NZ local time), causing widespread damage but only one fatality. An aftershock, the moment magnitude ( $M_w$ ) 6.3 Christchurch earthquake, occurred on February 22<sup>nd</sup>, 2011 at 12:51 pm (NZ local time) and caused 185 fatalities. The close proximity of the earthquake to the Central Business District (CBD) of Christchurch caused significant damage, with far greater shaking intensity occurring than was anticipated. These earthquakes, as well as other aftershocks, are part of the Canterbury Earthquake Sequence (CES) that ultimately affected over 300,000 people and caused damage to 100,000 residential properties (Rogers et al, 2013). The February 22<sup>nd</sup> earthquake was caused by a shallow oblique and reverse fault, the Port Hills Fault (previously unmapped) and its epicenter was located approximately 8 km southeast of Christchurch CBD with a hypocentral depth of about 4 km (GEER, 2011). The ground shaking was short (<10 sec) but intense, it was recorded accelerations up to 2.2g near the epicenter and up to 0.8g in the central city (Kaiser et al., 2011). Local soil conditions contributed to the ground shaking amplification, as the city of Christchurch is underlain by abandoned paleochannels of the Waimakariri River and its soil is composed by young loose and soft sediments with a shallow groundwater table with the bedrock over 200 m of depth (GEER, 2011).

The Christchurch earthquake caused liquefaction in large areas of the CBD, damaging buildings, infrastructure and lifelines (Bray et al, 2014). Two reinforced concrete buildings collapsed during the earthquake: the 1980's era Canterbury Television (CTV) Building, causing 115 fatalities; and the 1960's era Pyne Gould Co-operation (PGC) Building, causing 18 fatalities. Portions of the Christchurch CBD was cordoned for up to 2.5 years, as 47% of buildings were classified as unsafe or with restricted access. Buildings were evaluated, and in many cases demolished, before public access was granted to the CBD. The economic losses of this earthquake ascend to NZ\$40 billion (Potter et al., 2014).

The moment magnitude  $(M_w)$  7.8 Kaikoura earthquake occurred on November 14<sup>th</sup>, 2016 at 12:02 am (NZ local time) on the northeast coast of New Zealand's South Island. The epicenter was located 15 km northeast of the town of Culverden (70 km south of Kaikoura) with a hypocentral depth of 15 km. The earthquake rupture was complex; and it propagated about 150 km north-eastward, rupturing several mapped and unmapped structures within the Marlboro Fault Zone (MFZ). Unlike the Christchurch earthquake, this event caused surface ruptures, with vertical displacements of up to 7 m in the Kekerengu Fault (GEER, 2017). Vertical ground accelerations of 2.7*g* were measured at the Waiau Valley recording station; and peak horizontal ground accelerations of 0.27*g* were measured around Kaikoura. The shaking lasted for about 2 min. This earthquake caused 2 fatalities, one

from a house collapse and another from a heart attack (Stevenson et al., 2017). It caused extensive damage to buildings and infrastructure in the northeast of the South Island.

The earthquake caused tens of thousands of landslides in an area of 10,000 km<sup>2</sup> in North Canterbury and Marlborough; and over 200 landslide dams (Dellow et al., 2017). There were 85 landslides along the coastal highway, State Highway 1, which temporarily restricted access to Kaikoura. The Port of Wellington on the North Island was also damaged by the earthquake.

#### Report Charge

Recognizing the importance of the post-earthquake phase for developing resilience through the built environment, this report focuses on how New Zealand's communities took advantage of the opportunities that were presented in the wake of the earthquakes. The following discussion considers two dimensions of these opportunities: rebuilding with seismically enhanced infrastructure (Section 2) and reconfiguring the built environment to resiliently accommodate natural hazards and deepen community ties (Section 3). Section 4 addresses challenges that arose in the recovery process. Finally, Section 5 considers how these lessons may be applicable for communities seeking to anticipate and prepare for their own post-earthquake recoveries.

The report is written in the context of the three focal points of the National Civil Defense Emergency Management (CDEM) Strategy for recovering from seismic events: *risk reduction, readiness,* and *response.* Readiness and response refer to logistical preparation for managing the recovery, both at the individual and community level. While logistics can be developed at any time, the risk reduction dimension is most feasible in the wake of a disaster, when community desire to repair or replace damaged infrastructure provides an opportunity to build back better. Rebuilding in a thoughtful way can also contribute to a community's capacity for readiness and response.

#### 2 **OPPORTUNITIES TO REBUILD WITH ENHANCED STRUCTURES**

Every engineered structure is designed for a certain level of performance, whether implicitly through prescriptive codes or explicitly through performance criteria. With many structures damaged after an earthquake, there is an opportunity to reevaluate the desired seismic performance. Individual building owners, affected communities, and New Zealand as a whole have used a variety of strategies for enhancing the seismic performance of structures. These strategies include updates to seismic hazard provisions to reflect the tectonic setting, restrictions on construction typologies that did not perform well during the earthquakes, implementation of high-performance seismic resisting systems for low-damage design, and retrofit programs to upgrade existing buildings.

#### Changes to New Zealand's Seismic Design Provisions

The primary reason for the unanticipated extent and severity of damage in CES was an underestimation of the region's earthquake hazard. To demonstrate the underestimation, Figure 1(left) compares ground motion records from Christchurch to the design spectrum representing the 500 year return period earthquake. Not only do the records exceed the design spectrum at all periods, they even cross the solid line representing the 2500 year return period earthquake over a broad range of periods. In light of this, the Canterbury Earthquakes Royal Commission (CERC) recommended that the design provisions be increased to reflect the new knowledge regarding the seismicity of the Canterbury region. Per this recommendation, the earthquake loading specifications in NZS1170.5 increased the 500-year and 2,500-year spectra by approximately 36%, as shown in Figure 1(right).



Figure 1. Christchurch soft soils (soil Class D) design spectra comparison. (Left) Recorded acceleration response spectra in the 22 February earthquake (5% damped); solid red line is the geometric mean of four sites and the dashed and solid black lines are the 500- and 2500-year NZS1170 spectra, respectively (adapted from McVerry et al., 2012). (Right) Design spectra before and after the CES.

There were also changes for subsoil amplifications and the vertical loading spectra because of substantially higher vertical components of ground motions than were anticipated, and because the vertical component of the ground motion is frequently omitted from consideration during building design. For details on the derivation of design spectra parameters, hazard modeling and the New Zealand NSHM refer to McVerry et al. 2012 and the final report of the Canterbury Earthquake Royal Commission (Section 2 of Vol. 1, CERC, 2012). In addition to updates for the hazard characterization, there were modifications to the design of diaphragms and non-structural elements, increased inelastic torsional demands, and updates to the definition of ultimate limit state, associated with the onset of building collapse. A detailed discussion of these and other changes expected in an upcoming amendment of NZS1170.5 (expected 2019) are discussed in Jury et al., 2018. For a historic comparison of New Zealand's standards for seismic design of concrete buildings, see Fenwick ad MacRae, 2009.

#### Updated Design Standards for Hollow-Core Slabs

Precast construction, particularly, precast concrete floor diaphragms have dominated New Zealand's practice over the past few decades, following reduced prevalence of steel construction in the 1970s due to strikes by steel workers. Hollow-core slabs proved particularly vulnerable during the CES. For example, the hollow-core floor system of the Rehua building, located at the University of Canterbury, sustained substantial damage and was subsequently retrofitted. Furthermore, during the 2016 Kaikoura earthquake the hollow-core floor system of the NZ Statistics building partially collapsed highlighting the vulnerabilities these precast floor systems. The building was later demolished (Stuff News, 2018). Since then, other buildings have been or are under evaluation, while others have been permanently closed, such as the Wellington Central Library, due to precast floor vulnerabilities (see report by Aurecon, 2019).

Concerns regarding the vulnerabilities of hollow-core floors are not new. Prior to the CES, several deficiencies of various precast floor systems had been identified; furthermore, concerns with the performance of hollow-core floors were first raised in New Zealand after the observed failures of hollow-core floors during the 1994 Northridge earthquake (see Corney et al. 2014). Fenwick et al. (2010), provides a summary of the potential failure mechanisms of hollow-core units, including: loss of support; positive and negative moment flexural failures near supports; diagonal tension failure, following a reduction in shear strength due to flexural

cracking near the support; splitting shear failures, due to differential displacement between a beam and adjacent hollow-core unit; and torsional failure. Following the CES and the 2016 Kaikoura earthquake, New Zealand's design provisions (NZS3101:2006 - Concrete Structures Standard) were amended to reduce the vulnerability of hollow-core systems. Among the changes recommended by the Structural Engineering Society of New Zealand and CERC are:

1) Increased minimum floor topping thickness to 75mm (~3 in.)

2) Prohibited the use of non-ductile reinforcing mesh

3) Hollow-core units must be supported away from the edge of the beam on low friction bearing strips.

4) Support details for hollow-core slabs must be able to sustain 1.5 times the interstory drift level and ensure the unit remains seated during design level earthquake.

For a detailed discussion of the seismic assessment of hollow-core floor diaphragms see Appendix C5E - Assessing Precast Concrete Floor Systems, of the Technical Proposal to Revise the Engineering Assessment Guidelines for detailed seismic assessment of concrete buildings (C5-1A, 2018), and the report by Fenwick et. al., 2010.

#### Implementation of Low Damage Design Techniques

After the devastating outcomes of the CES, improved building performance and earthquake resilience were at the forefront of the recovery and reconstruction in Christchurch. Furthermore, structural engineers were more influential during the design process and clients more receptive to low-damage design solutions (as opposed to the minimum code requirement for Life-Safety). The new resilience-conscious market has increased the use of seismic isolation, buckling restrained braces, viscous dampers and other low-damage technologies (Campbell, 2018). While in Christchurch, the LFE participants encountered several buildings and other structures that implemented low damage design technologies. The Rehua building at the University of Canterbury (Figure 2a), originally a reinforced concrete moment frame building, was retrofit with a new steel framing system, braced frames, and viscous dampers, as shown in Figure 2b. Several other buildings on the University of Canterbury campus incorporated braced frames, seismic gaps, and other earthquake resistant design features. Similarly, new construction projects throughout Christchurch and Wellington are targeting low damage as an enhanced seismic performance criterion. In Christchurch, the Ernest Rutherford building and the parking garage, shown in Figure 3a and b, incorporate buckling restrained braces (BRB). In Wellington, the new PwC Center building features base isolation (Figure 4).





b)

Figure 2. Rehua building at the University of Canterbury. a) Rehua building prior to retrofit (Pettinga, D., 2019); b) New steel framing including viscous dampers (top) and braces (bottom)



Figure 3. Buildings in Christchurch Implementing Buckling Restrained Braces. a) Ernest Rutherford Building, University of Canterbury. b) Multi-Story Parking Structure in Christchurch CBD.



Figure 4. Base Isolated Building in Wellington's Waterfront. a) PwC Center; b) Seismic Isolation Gap.

Despite increased use of low damage building technologies in New Zealand, the adoption of low damage design faces several challenges, among them, the lack of design guidelines for enhanced performance of normal-use buildings. The Structural Engineering Society of New Zealand is spearheading a guidance document to develop a framework for a standard approach to low damage design (Campbell, 2018). The implementation of low damage design in New Zealand is expected to increase in the coming years.

#### Performance and Opportunities for Improving Lifelines

Lifelines play a key role in community resilience, and major disasters such as the 2011 Christchurch earthquake can provide opportunities for improvement. After the CES, water, communications and electric infrastructure were significantly damaged; however the extent of damage and service interruption varied. Despite the damage, the restoration of lifelines and services was remarkable, particularly the communications and electric service which were restored within days of the events; details of the performance of electric infrastructure are provided in Kwasinski et al., 2014. The successful performance of the utility lifelines in New Zealand is in great measure attributed to a study on the vulnerabilities of lifelines conducted in the 1990s (refer to Risks and Realities, 1997), highlighting the importance and benefits of planning and preparation.

During the 2016 Kaikoura earthquake, transportation routes and railroad services were substantially impacted, whereas power and communications were restored within two days in the Northern Canterbury region, and within 24 hours in Wellington (Stevenson et al., 2017). The North Canterbury Transport Infrastructure Recovery (NCTIR) consortium was organized to restore the road and rail networks from the damage caused by the earthquake to the Main North Line railway and SH1 (Kaikoura earthquake response). State Highway 1 was blocked off and the main north line railway between Picton and Christchurch was disrupted. Inland roads such as Route 70 were also disrupted, making Kaikoura inaccessible from all directions (Davies et al, 2017). NCTIR increased functionality by straightening curves and adding scenic points (Figure 5: Ohau Point) along the highway. When rebuilding, the designs included both large barricades and culverts to direct debris under the road, protecting it from landslides (Figure 6).



Figure 5. (Left) New Telecommunication Lines Along State Highway; (Right) Oahu Point.



Figure 6. State Highway 1 Realignment. a) After 2016 Kaikoura Earthquake; b) After Reconstruction and Realignment. (Photos from NCTIR, 2019).

An unexpected benefit of the strong shaking and during the Kaikoura earthquake is that it caused the seafloor to rise, creating new beachfront. This allowed the (NCTIR) to realign the severely affected State Highway 1 as shown in Figure 6. Increased elevation along the coast provides an additional buffer for the coastal road against the effects of long-term sea level rise. The extensive reconstruction and mitigation work provided several opportunities to improve the function along the highway, such as expanding the telecommunications reach, as shown in Figure 5.

The tourism industry in Kaikoura, severely impacted by the earthquake, took advantage of opportunities presented by reconstruction. The tourism industry in Kaikoura was severely impacted following the earthquake because the access highways were damaged in many locations. This was also an opportunity to rebuild the roads in such a way that it simultaneously supports communities and wildlife preservation. Part of a road section was widened to serve as a vista point (Figure 5) from which you can see the native seal colony along the coastlines. The debris culverts under the highway also provide a passage for the seals to access sunbathing areas on the inland side of the road. This simple initiative allows for increased economic activities for local communities and supports wildlife conservation.

#### Seismic Evaluation and Retrofit Programs

When buildings and infrastructure need to be rebuilt, there is an opportunity to build back better, recognizing that the community will benefit from enhancing the performance of its new buildings. The public's heightened earthquake awareness also presents an opportunity to address the vulnerability of existing buildings unaffected by the disaster. While addressing the existing building stock is much more difficult than changing new design requirements, New Zealand recognized the importance of such an effort. To this end the Ministry of Business, Innovation and Employment (MBIE) enacted a methodology to identify earthquake-prone buildings (EPB), through the Building (Earthquake-prone Buildings) Amendment Act 2016, which amended the Building Act of 2004. The structure of the framework for managing earthquake-prone buildings is summarized in Figure 7. The Engineering Assessment Guidelines provides the technical basis for conducting the seismic assessment of existing buildings and results in a seismic rating based on the expected performance of a new code-compliant building or the New Building Standard (NBS). The guidelines establishes that any evaluated building that meets 33% or less of the NBS, is considered an earthquake-prone building and included in the public EPB register accessible online. EPBs must be retrofit to more than 33% of NBS.



Figure 7. Structure of the system for managing earthquake-prone buildings (MBIE, 2017).

For further details, the reader is referred to MBIE's EPB methodology (MBIE 2018). Within this framework are contained the Engineering Assessment Guidelines for the Seismic Assessment of Existing Buildings (EAG, 2017) which includes: Initial Assessment of Buildings; Detailed Seismic Assessment of Potentially Earthquake-prone Buildings; and Detailed Seismic Assessment of buildings not within the EPB Methodology.

Many unreinforced masonry (URM) buildings were severely damaged during the CES and the 2016 Kaikoura earthquake. These earthquakes highlighted the particular vulnerabilities of chimneys, parapets, gable walls and out of plane wall failures in URM buildings and the falling hazard they pose to building occupants and pedestrians. These vulnerabilities were known prior to the CES and at the time of the M6.3 Christchurch earthquake, there were URM buildings that had been subjected to various levels of seismic strengthening. However, the observed damage after the CES was severe. Ingham and Griffith (2011b) indicate that approximately 97% of the URM buildings that had not been seismically strengthened were severely damaged or collapsed and that approximately 63% of all URM buildings. Furthermore, 60% of URM buildings strengthened to less than 33%NBS sustained major damage or collapsed; similarly, URM buildings strengthened to 34-67%NBS, 67-100% and 100%NBS, 72%, 24%, and none of the buildings were seriously damaged or collapsed, respectively (Ingham and Griffith, 2011b). The reported %NBS by Ingham and Griffith (2011b) were based on the existing guidelines (NZSEE, 2006); for further details on the vulnerabilities of URM buildings in New Zealand and their performance during the CES refer to the report by Ingham and Griffith (2011a,b).

After the extensive damage to URM building during the CES and the Kaikoura earthquake, in February 2017 the MBIE established an initiative to improve the seismic performance of URM buildings in New Zealand enacted by a council order amending the 2004 Building Act. This initiative required building owners to secure unreinforced masonry parapets and facades by the end of September 2018. For this purpose, the Government and Wellington City Council contributed a total of \$3 million NZD to help Wellington building owners comply with the strengthening requirements within the required time frame. The fund contributed 50% of costs up to \$25,000 for buildings 1–2 storeys, and 50% of costs up to \$65,000 for 3 or more storeys (Wellington City Council Web). A guide providing support to building owners, engineers, and councils to on complying with the requirements of the seismic strengthening initiative was published in 2017 with its newest revision published in arch 2018 (MBIE, 2018).

Concerns with precast floor systems has led to building closures (Wellington Central Library) and may potentially lead to future retrofit programs. Research on addressing the vulnerabilities of hollow-core and other precast floor systems (double tees) is ongoing at the University of Auckland, and may lead to future updates to design and retrofit practices in New Zealand. Most of the retrofitted URM buildings are heritage buildings, such as the Wellington Town Hall, and thus require special consideration and protections. However, not all buildings with vulnerable precast floor systems are classified as heritage buildings. For non-heritage buildings, the decision to retrofit instead of demolishing and rebuilding must be decided on a case by case basis. For example, the decision to retrofit Canterbury University buildings was contentious because it did not have special considerations allocated for heritage buildings. It was debated that there would be better value for money if the existing building was demolished and replaced by a newer building with an enhanced seismic protective system. The decision was made to retrofit because the cost was cheaper than the estimated cost of demolition and constructing a new building.

#### 3 OPPORTUNITIES TO RECONFIGURE THE BUILT ENVIRONMENT

The previous section discussed how New Zealand is rebuilding with enhanced structural performance in order to develop resilience and facilitate recovery after the next earthquake. However, moving the community's built assets out of harm's way is equally important in reducing risk. Once again, the aftermath of an earthquake provides an opportunity to reconfigure the built environment to accommodate that natural hazards that exist, as well as provide physical spaces where the community can deepen the ties that hold it together. Several examples from Christchurch's reconfiguration are presented below.

It is estimated that around 10,000 houses were demolished after the earthquake and as many as 100,000 buildings needed to be repaired after the 22 February 2011 earthquake in Christchurch (Tait, 2011). Many of the demolished buildings were within the cordoned CBD, significantly impacting the urban fabric of the city centre. While there are temptations to return the structures and community spaces to pre-event conditions, forethought in the rebuilding process can lead to alternative strategies that reconfigure the built environment in ways that improve the community and the resilience of the city. The scale of the damage provided an opportunity to completely reconfigure the urban form of the city. In many ways, Christchurch's current CBD does not resemble the previous iteration. For one, the Christchurch Central Recovery Plan (CERA 2012) set new height restrictions at 28m (~7 stories) and 17m (~4 stories) for the core and fringes of the CBD, respectively. While this change is relevant to earthquake risk and the potential for a damaged tall building to require an extensive cordon (see the Challenges section), the primary stated purpose of these reduced heights was a more livable, human-scale city. The CBD has also shrunk considerably from the east side and there is a large commercial development along the river (Figure 8, left). This development is compact and is aesthetically pleasing. In addition, many of these new buildings are being built for better seismic performance than the code's minimum life safety requirement. Reducing the damage these buildings experience to keep them functional soon after the next earthquake will enable faster recoveries for the people, communities, and institutions that occupy them.



Figure 8. Riverfront commercial development (left) and the Emergency Operations Center (right)

Reorganizing the built environment can also facilitate the logistical reorganization required to prepare for the post-event response (one of the Emergency Management Strategy's 3Rs that support planning for recovery). Christchurch's new Emergency Operations Center (EOC) now provides a space to integrate the New Zealand Police, St. John, Fire Emergency, and Christchurch City Council all in one building. By bringing these organizations together, the EOC (Figure 8, right) will be a world leading operating center with an integrated, emergency readiness, response and recover transition capability for coordinating local and regional

emergencies at first hand (EOC, 2016). It is also seismically isolated, which increases the likelihood of functionality immediately after a major seismic event. Immediate functionality for the emergency operations center is crucial for effective, rapid response in the immediate aftermath of an earthquake.

Tūranga, the Christchurch Public Library (Figure 9, left), was also a major CBD building project designed to bring all facets of the community together. It was built so that the people of Christchurch would have a public and safe place to gather, be creative, study, and enjoy each other and their community. In particular, its recurring architectural and design themes highlight and celebrate Maori Culture in many of its spaces. Tūranga was intended to host anchor projects that build community, and it contains playrooms for children to enjoy, study areas for everyone, reading stands, conference rooms, and creative spaces. On the library's opening day, many residents in the suburbs re-entered the CBD for the first time since the earthquake and families expressed joy in having public spaces where their children were welcomed. To improve performance during an earthquake, the building was designed with an enhanced seismic resistant system, which includes: steel moment resisting frames, post tensioned concrete rocking walls, U-Shaped flexural Plates, and lead extrusion dampers.



Figure 9. Turanga, Christchurch Public Library (left) and the Margaret Mahy Playground (right)

Another project in the CBD explicitly welcomes children into the fabric of the community, while also reorganizing the built environment to accommodate flooding on the bank of the Avon River. Post-earthquake silt in the river has changed the flooding hazard so damaged office building in the northwest corner of the CBD has now been replaced with the Margaret Mahy Playground (Figure 9, right). As a generation born after the earthquake, children lost their sense of place and ownership in the central city; this space is an attempt to rebuild the lost connection, while simultaneously reducing risk.

For the adults who were familiar with the pre-earthquake CBD, the loss of 80% of the buildings was accompanied by a jarring loss of their sense of place. Blocks that had once contained tall buildings were suddenly vacant. One of the first attempts to regain a sense of place was an organic community project now known as the "Dance-O-Mat." A washing machine was rigged up an auxiliary cord, speakers, and stationary bikes that generated electricity to create an open air dance floor. An updated form of the Dance-O-Mat remains to this day (without the bikes, now that electricity is available again) (Figure 10, left). Christchurch recognized the value of community spaces in the vacant lots and now facilitates innovate uses through Gap Filler, a charitable trust that sprang up for this purpose. Other public spaces in the CBD include a mini-golf course made from reclaimed artifacts in the city, a skate park, and a hammock forest (Figure 10, middle).



Figure 10. Dance-O-Mat in a vacant lot (left), a sign in the CBD pointing to public spaces (middle), plans to revitalize the Red Zone as a recreational area (right)

Outside of the CBD, liquefaction in residential neighborhoods around the river caused significant ground movement, as is shown in Figure 11, leading to unstable foundations and damaging major infrastructure such as water and sewage lines (Christchurch Earthquake, 2011). The current conditions and future risk make these lands, now known as the Red Zone, not suitable for rebuilding; and much of the area was left as is. The fact that this damage occurs raises caution regarding permitting land development in known risk prone areas and the consequences of doing so. But it also offers opportunities to apply risk-based land use planning so that such disastrous outcomes are not repeated in the future. Plans are currently under development for new recreational space in the Ōtākaro Avon River Corridor (Figure 10, right) in order to strengthen the connection between people, the river, and the land.



Figure 11. Damaged caused by liquefaction in Christchurch

#### 4 CHALLENGES IN RECOVERY

The quick succession of the large magnitude September 2010 and February 2011 earthquakes in Christchurch and ongoing shaking from multiple aftershocks posed many challenges for the recovery of Christchurch. In the city of Christchurch, hundreds of commercial buildings and civic assets were destroyed, around 168,000 houses were damaged, and there was an estimated more than NZ \$40 billion dollars of damage, or about 20% of the New Zealand Gross Domestic Product, as a result of the earthquake. In addition, over 750,000 insurance exposure claims were made, with an estimated total of insured damages equaling over NZ \$30 billion (Potter, 2015). The strong shaking that resulted from the November 2016 Kaikoura earthquakes had a large impact on the city of Wellington. Although the impact and scale of the disaster was smaller for the city of Wellington when compared to the damage in Christchurch, both cities required significant financial investment to recover.

#### Cordons

Because of the extensive damage to the Christchurch CBD, cordons were established after both Christchurch earthquakes to restrict access to the area. These consisted mainly of fences and guarded perimeters. After the September 2010 earthquake, local authorities established cordons around most of the city center and they were gradually reduced and fully removed about a week after the earthquake (Chang, 2014). After the February 2011 earthquake, a cordon was established around the whole CBD. It was reduced in size by about half by July of 2011. Figure 12 shows the extent of the CBD cordon over time. These cordons were justified to the public on the basis of safety. The implications of an inaccessible CBD and loss of confidence that the CBD will ever recover, which resulted from the cordons, made it challenging for the city to recover quickly. Many businesses were inaccessible or the buildings that housed them were torn down. Stevenson et al., found that following the Christchurch earthquakes, 32% of businesses had staff that were forced to temporarily relocate, and 13% of businesses had staff that were forced to permanently relocate worked in the CBD prior to the earthquake.

Initially, pressure from the public to reduce the size of the cordons was strong, but this pressure slowly tapered off, and the cordons were accepted by the public following aftershocks. About 50,000 central city jobs were displaced as a result of the cordon implementation; and many questions were raised about the long-term viability of the CBD (Chang, 2014). While most cities develop organically, 'the blueprint' for a rebuilt Christchurch did not allow for such development. The new plans called for sectoral development, a very top down approach of zoning areas based on their use. Smaller businesses were driven out of the market due to spatial requirements that encouraged bigger businesses. This approach hindered organic mixed-use planning, which has been shown to be effective and necessary for continued activities and supporting vitality of city centres around the world.



Figure 12. Map of the Central Business Cordon after the 2011 Christchurch Earthquake (Hulsey et al. 2018).

Following the November 2016 Kaikoura earthquakes, cordons were erected around a significant part of the Wellington downtown area. However, these cordons only remained in place until about a week after the event (Stevenson, 2017). While these cordons had a significant impact on the city, they were far less disruptive than the Christchurch earthquake because they remained in place for a much shorter time. However, for both Christchurch and Wellington, there was a huge disruption in productivity for the firms affected by the cordons, both while the cordons were in place and after they were removed. When the cordons were in effect, alternative accommodations had to be made for people employed in the cordon, and the new workspaces weren't at the same standards as the original workspaces (Deloitte, 2017). After the cordons were removed, some people had a sense of fear for the safety of their building during the workday.

#### Heritage Buildings

Many heritage buildings in the CBD were unreinforced masonry buildings and were significantly affected by the 2010 and 2011 earthquakes and their aftershocks. A total of 100 heritage buildings were assessed in a report completed by the New Zealand Historic Places Trust to the Canterbury Earthquakes Royal Commission (NZHPT, 2012). After the earthquakes and aftershocks, three of these buildings collapsed, 51 buildings were deemed severely damaged and nearly all of those 51 buildings had to be demolished. In addition, another 32 of these buildings were moderately damaged. Many of the damages to these buildings impacted the community and their sense of local identity because of the major historical significance, resulting in many challenges when it came to recovery. The discussion about whether or not these buildings could be restored, if they should be restored, or if they should be torn down, sparked discussion with the community and slowed down the process of recovery. An example of this is the Christchurch Cathedral, located at the center of the city, surrounded by the Cathedral Square. Figure 13 (left) shows the state of the Christchurch Cathedral, eight years after the 2011 earthquake. The cathedral sits in the middle of the city, deserted, and some consider the damaged structure as distracting to the progress taking place in the rest of the city. Nevertheless, when the Anglican church revealed their intention to tear down the remains, there was backlash over a private entity unilaterally making this decision for such a symbolic building, especially since public money has already been directed to its maintenance over the decades. The result was a mire of lawsuits and frustration on all sides. Seeing this challenge of making post-earthquake decisions on symbolic buildings, Wellington has preemptively solicited public input on how to handle the Wellington Town Hall (Figure 13, right). The building is listed as a Category I Historic Place under the New Zealand Historic Places Trust and is famous for hosting many famous artists, including the Beatles. In response to the public's preference to retrofit and restore the building, plans are underway to install foundation screw piles and base isolation, while simultaneously updating the interior acoustics. Because the Town Hall is a public building, unlike the Christchurch cathedral which is symbolic but

simultaneously a privately owned religious institution, these efforts are more straightforward. A severely damaged Town Hall would still be a delicate crisis to resolve, so Wellington's efforts to engage the public in the decision ahead of time is admirable.



Figure 13. (Left) The Christchurch Cathedral as of May 2019. (Right) Wellington Town Hall

With respect to the many damaged buildings in Christchurch, some buildings were repaired and restored while others were demolished. Figure 14 shows the New Regent Street Precinct located in Christchurch. The New Regent Street Precinct is a pedestrian mall built in the early 1930s with a Spanish Mission architectural style. The February 22 earthquake severely damaged the block, and because of limited resources and many delays in construction, the whole mall was not fully repaired. All the historic facades were repaired but some of the lots are completely empty behind the facade. After the mall reopened, many storefronts remained empty for a long time because new tenants were not interested in renting the spaces. This was a common issue throughout the Christchurch CBD.



Figure 14. New Regent Street Precinct shopping mall in Christchurch with repaired historical facades.

The Kaikoura earthquake damaged heritage buildings in Wellington, and the city also struggled with recovery and repairs of the buildings due to limited resources and economic funding (Deloitte, 2017). However, the damage seen in Wellington was not as bad as what was seen in Christchurch, so the recovery process was more rapid than in Christchurch.

#### Retrofits

Another challenge for both recovery and resilience is the balancing act between physical resilience and economic resilience. The recent New Zealand earthquakes have served as a reminder of the importance of retrofitting buildings for safety in future earthquakes. Some estimates suggest that retrofitting a building to code standard can sometimes cost 30-40% more than constructing a new building (Beaupre, 2014). Therefore setting the appropriate threshold for requiring retrofits is a difficult political task. The EPB designation was set as 33% of the capacity required for new buildings, simultaneously leaving many buildings far below the minimum performance of new buildings and imposing costly requirements on those who were unfortunate enough to own an EPB. There is no simple solution, especially for heritage buildings where the cultural value must be balanced with the seismic performance and retrofit cost.

#### 5 APPLYING THE LESSONS FROM NEW ZEALAND TO COMMUNITIES WORLDWIDE

In light of the previous observations on New Zealand's recovery in Christchurch, Kaikoura, and Wellington, the following discussion considers how communities outside of New Zealand can anticipate and prepare for their own post-earthquake recoveries.

1. Consider the opportunities for developing community resilience that are available in the post-earthquake environment.

The New Zealand recoveries exemplified the benefits of recognizing and taking advantage of opportunities to develop community resilience by changing the built environment, both through enhancing the seismic performance of individual structures and through reconfiguring the community layout. The opportunities were particularly prominent in Christchurch and Kaikoura, where the scale of the destruction provided space to re-imagine the fabric of the community. It can be tempting to rebuild as quickly as possible by using the pre-earthquake configuration as the blueprint. One way to handle the multiple stressors of this process in the post-earthquake environment is to anticipate and prepare for the opportunities ahead of time. Seattle's Disaster Recovery Framework (2015) is an example of this, in which the city is engaging with the community to determine what shared values will be priorities after the earthquake. While the exact nature of the destruction that will occur and associated opportunities that will arise is unknown, Seattle is developing an impressive wish-list of what they would do if they had a clean slate, including the most effective, resilient configuration for the Port of Seattle.

At the same time, care should be taken that the new measures are effective, especially with regards to new construction techniques. After the problems with non-ductile concrete in the Sen Fernando earthquake in 1971, welded steel moment frames replaced reinforced concrete as the most popular lateral force resisting system, only to discover their deficiencies in the 1994 Northridge earthquake. Similarly, New Zealand's hollow core construction is now proving to be a significant vulnerability. It is important to test, imagine, and consider how to improve the chances that the new construction replacing the old will stand the test of time.

#### 2. Consider the appropriate level of building performance for code requirements

In New Zealand, as in most of the world, building to a structural design codes provides a minimum life safety requirement. This approach protects the lives of building occupants during a big earthquake rather than the function of the building itself. Therefore the expected performance during the design earthquake includes significant damage that may not be practical or economical to repair. The loss of these buildings'

functionality during repairs or complete replacement would continue to disrupt the community long after the earthquake shaking stops.

In recognition of this, changing the code's intended performance level is an ongoing discussion both in New Zealand (Mitchell, 2019) and in the United States. The US Congress tasked the National Institute of Standards and Technology (NIST) and the Federal Emergency Management Agency (FEMA) with jointly recommending options for "improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake reoccupancy and functional recovery time." (National Earthquake Hazards Reduction Program Reauthorization Act of 2018) Similarly, Assembly Bill 393 (2019) is currently moving through the California legislature "to consider whether a 'functional recovery' standard is warranted for all or some building occupancy classifications." One reason why these efforts are still discussions, rather than progressing to code changes, is that switching to functional recovery standards is a complex issue. While the technology and design methodologies are available for low-damage designs, there are barriers to bringing them into the mainstream, both technically in terms of how to define a minimum functionality standard and socio-economically in terms of balancing current needs against post-earthquake needs. Nevertheless, New Zealand's experience is a powerful indicator of the importance of having functional buildings after an earthquake to reduce community impacts and speed recovery.

#### 3. Consider existing community assets

Changing the building codes to ensure functionality after an earthquake would improve the performance of all new buildings yet it does not address the performance level of the existing buildings that make up the majority of a community's building stock. Therefore it is also important for communities to be familiar with the vulnerabilities that exist and consider how to address them. New Zealand is handling this through their EPB designation, in which buildings with less than 33% of the code-level capacity are identified and required to be retrofit or demolished.

The implementation of this program highlights two important aspects for other communities to consider. First, in order to enact a retrofit program in which the affected buildings are identified and the owners contacted, the community must have some level of familiarity with the vulnerability of the existing building stock. This is no simple task. With the introduction of Assembly Bill 429 (2019), California is currently grappling with whether it is appropriate or feasible to require cities and counties to compile an inventory of seismically vulnerable buildings. For the most effective policies, an inventory would need to include the community function of each building, in addition to its level of vulnerability. With that information, mandatory retrofit programs could be tailored to promote resilience of community functions, rather than simply requiring every deficient building to be retrofit.

A second key aspect of New Zealand's EPB program is setting the appropriate threshold for requiring a retrofit (33% for EPB) and setting the minimum required level for retrofits (reaching at least 34% for EPB). One early plan for the program set the threshold at 66% (per informal discussions during the LFE trip). However, after future discussion, the wide-spread effect and cost of such a threshold was deemed too high. This points to the importance of making such decisions as a community, by balancing current and future priorities.

As communities prepare for post-earthquake recovery it is important to have far reaching, collective discussions on the desired performance of the built environment. While the performance of new buildings and

existing buildings are certainly related, the inertia of the existing building stock increases the challenges associated with improving their performance. This difficulty underscores the importance of thinking carefully about the minimum requirements for new buildings which, once built, will become existing buildings and of making the most of post-earthquake opportunities to fundamentally change the fabric of the built environment.

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#### 7 **R**EFERENCES

Aurecon (2019). "Wellington Central Library Hollow-Core Assessment Report". Report to Wellington City Council. https://wellington.govt.nz/services/community-and-culture/libraries/central-library-closure

A.B. 393 Building codes: earthquake safety: functional recovery standard, 2019-2020 Reg. Sess. (California 2019) https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill\_id=201920200AB393, accessed July 1, 2019

A.B. 429 Seismically vulnerable buildings: inventory, 2019-2020 Reg. Sess. (California 2019) https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill\_id=201920200AB429, accessed July 1, 2019

Beaupre, A., DeMarco, M., Dutra, T., Gogichaishvili, A., Haley, D., Hyman, A., Calvetti, N. K., & Potter, J. (2014). "Life Safety vs. Preservation of Community and Heritage Buildings in the Wellington Region." Worcester Polytechnic Institute.

Bray, J., Cubrinovski, M., Zupan, J. and Taylor, M. (2014). Liquefaction Effects on Buildings in the Central Business District of Christchurch. Earthquake Spectra, 30(1), 85-109.

C5-1A (2018). "Part C - Detailed Seismic Assessment of Concrete Buildings C5-1A: Technical Proposal to Revise the Engineering Assessment Guidelines". ISBN:978-1-98-857036-5 (Online)

Campbell, P. (2018). "Proposed Low Damage Design Guidance - A NZ Approach." 17th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience, Queenstown, New Zealand.

CERC (2012). "Final Report of the Canterbury Earthquake Royal Commission", Volumes 1-7.

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. 513-532.

"Christchurch Earthquake - an overview." (2011). Retrieved from https://web.archive.org/web/20110409084145 /http://www.ipenz.org.nz/ipenz/forms/pdfs/ChChFactSheets-Overview.pdf

Canterbury Earthquake Recovery Authority (2012). Central City Recovery Plan. Christchurch: Canterbury Earthquake Recovery Authority

Corney, S. R., Henry, R. S., and Ingham, J. M. (2014). "Performance of precast concrete floor systems during the 2010/2011 Canterbury earthquake series." Magazine of Concrete Research, Thomas Telford Ltd, 66(11), 563–575

Davies et al. (2017). "Transport Infrastructure Performance and Management in the South Island of New Zealand, During the First 100 Days Following the 2016 Mw 7.8 "Kaikōura" Earthquake." Bulletin of the New Zealand Society for Earthquake Engineering. 50. 271-299.

Dellow, G.D., Massey, C.I., Cox, S.C., Archibald, G.C., Begg, J.G.; Bruce, Z.R., Carey, J.M., Davidson, J., Della-Pasqua, F.N., Glassey, P., et al. (2017). Landslides caused by the MW 7.8 579 Kaikoura earthquake and the immediate response. Bulletin of the New Zealand Society for 580 Earthquake Engineering, Kaikoura Earthquake Special Issue, 50, 106-116.

Deloitte (2017). "The Forgotten Impact, Kaikoura Earthquake: Wellington Still Paying the Price."

Disaster Recovery Framework (2015). City of Seattle, Seattle Office of Emergency Management. http://www.seattle.gov/Documents/Departments/Emergency/PlansOEM/Recovery/SeattleDisasterRecoveryFra mework7-7-15v2.pdf

EAG (2017). "Technical Guidelines for Engineering Assessments". Ministry of Business, Innovation and Employment, the Earthquake Commission, the New Zealand Society for Earthquake Engineering, Structural Engineering Society and the New Zealand Geotechnical Society. Wellington, NZ. http://www.eq-assess.org.nz/

"EPB Register." Retrieved from https://epbr.building.govt.nz/, accessed June 30, 2019

EOC (2016). Emergency Operations Centre Collaboration Tool. New Zealand Government Electronic Tenders Service.

Fenwick, R., Bull, D., and Gardiner, D. (2010). Assessment of Hollow-Core Floors for Seismic Performance. Christchurch, New Zealand

Fenwick, R., and MacRae, G. (2009). "Comparison of New Zealand Standards Used for Seismic Design of Concrete Buildings." Bulletin of the New Zealand Society for Earthquake Engineering, 42(3), 187–203.

"Gap Filler." Retrieved from https://gapfiller.org.nz/, accessed June 30, 2019

Geotechnical Extreme Events Reconnaissance - GEER (2011). Geotechnical reconnaissance of the 2011 Christchurch, New Zealand Earthquake. Report of the National Science Foundation-Sponsored Geotechnical Extreme Events Reconnaissance (GEER) Team. Version 1: November 8, 2011. (www.geerassociation.org)

Geotechnical Extreme Events Reconnaissance - GEER (2017). Geotechnical reconnaissance of the 2016 Kaikoura, New Zealand Earthquake. Report of the National Science Foundation-Sponsored Geotechnical Extreme Events Reconnaissance (GEER) Team. Version 1: June 10, 2017. (www.geerassociation.org)

Hulsey, A. M., Deierlein G. G., Baker, J. W. (2018). "Quantifying the Post-Earthquake Downtime Induced by Cordons Around Damaged Tall Buildings." Proceedings of the 11th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Los Angeles, CA.

Ingham, J. M., and Griffith, M. C., (2011a). "The Performance of Unreinforced Masonry Buildings in the 2010–2011 Canterbury Earthquake Swarm", Report to the Canterbury Earthquake Royal Commission. https://canterbury.royalcommission.govt.nz/documents-by-key/20110920.46

Ingham, J. M., and Griffith, M. C., (2011b). "The Performance of Earthquake Strengthened URM Buildings in the Christchurch CBD in the 22 February 2011 Earthquake", Addendum Report to the Canterbury Earthquake Royal Commission. https://canterbury.royalcommission.govt.nz/documents-by-key/20110920.46

Jury, R., Bull, D., and MacRae, G. (2018). "NZ LOADINGS STANDARD (NZS1170.5) 2016 AND 2018 MODIFICATIONS TO STRUCTURAL CLAUSES FOR INCREASED SEISMIC RESILIENCE." 17th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience, Queenstown, New Zealand.

"Kaikōura earthquake response: Project introduction." New Zealand Transport Agency. Retrieved from https://www.nzta.govt.nz/projects/kaikoura-earthquake-response/, accessed June 30, 2019.

Kaiser, A., Holden, C., Beavan, J., Beetham, D., Benites, R., Celentano, A., Collett, D., Cousins, J., Cubrinovski, M., Dellow, G., Denys, P., Fielding, E., Fry, B., Gerstenberger, M., Langridge, R., Massey, C., Motagh, M., Pondard, N., McVerry, G., Ristaua, J., Stirling, M., Thomas, J., Umaa, S. R., and Zhaoa, J., 2012. The Mw 6.2 Christchurch earthquake of February 2011: preliminary report, New Zealand Journal of Geology and Geophysics 55, 67–90.

MBIE (2017). "EPB methodology." Ministry of Business, Innovation and Employment.ISBN 978-1-98-851790-2

MBIE (2018). "Securing parapets and facades on unreinforced masonry buildings." Ministry of Business, Innovation and Employment. ISBN 978-1-98-851724-7

McVerry, G. H., Gerstenberger, M. C., Rhoades, D. A., and Stirling, M. W. (2012). "Design Spectra for the Reconstruction of Christchurch." 15th World Conference on Earthquake Engineering, Lisboa, Portugal.

Mitchell, R. (2019). "State of shock: How our buildings save lives but little else". Stuff News, New Zealand. https://www.stuff.co.nz/national/nz-earthquake/113448477/state-of-shock-how-our-buildings-save-lives-but-littl e-else

National Earthquake Hazards Reduction Program Reauthorization Act of 2018, S. 1768 Section 8 (2018). https://www.congress.gov/bill/115th-congress/senate-bill/1768/text

NCTIR (2019). "Kaikōura Earthquake Recovery: NCTIR - Carving Enduring Connections". Presentation to Learning From Earthquakes Travel Study Program. May 2019.

NZHPT (2012). "Heritage buildings, earthquake strengthening and damage." New Zealand Historic Places Trust Pouhere Taonga.

NZS1170.5:2004 (2016). "Structural design actions Part 5 Earthquake actions – New Zealand, New Zealand", Standard NZS1170.5:2004, Incorporating Amendment 1.

Pettinga, D. (2019). "Rehua - Seismic Strengthening: Retrofit of a Ductile RC Moment-Frame with Viscous Damping and BRBs". Presentation to Learning From Earthquakes Travel Study Program. May 2019.

Potter, S.H., Becker, J.S., Johnston, D.M., & Rossiter, K.P. (2015). An Overview of the Impacts of the 2010-2011 Canterbury Earthquakes. International Journal of Disaster Risk Reduction. 14. 6-14.

Risks and Realities. (1997). "Risks and Realities: A Multi-disciplinary Approach to the Vulnerability of Lifelines to Natural Hazards". Report of the Christchurch Engineering Lifelines Group. Centre for Advanced Engineering, University of Canterbury Christchurch New Zealand. ISBN 0-908993-12-9

Rogers, N., K. Williams, M. Jacka, et al. (2014). Geotechnical aspects of disaster recovery planning in residential Christchurch and surrounding districts affected. Earthquake Spectra, 30(1), 493-512.

Stevenson, J. R., Becker, J., Cradock-Henry, N., Johal, S., Johnston, D., Orchiston, C., and Seville, E. (2017). "Economic and social reconnaissance: Kaikōura earthquake 2016." Bulletin of the New Zealand Society for Earthquake Engineering, 50(2), 343–351

Stevenson, J.R., Vargo, J., Seville, E., Kachali, H., McNaughton, A., & Powell, F. (2012). The recovery of Canterbury's organizations: A comparative analysis of the 4 September 2010, 22 February and 13 June 2011 earthquakes, Resilient Organizations Research Report, Christchurch.

Stuff News. (2018). "Expert panel told Wellington's Statistics House not built to design". July 4, 2018. https://www.stuff.co.nz/business/105234869/expert-panel-told-wellingtons-statistics-house-not-built-to-design

Tait, Maggie. (2011). "Christchurch Earthquake: 100,000 homes damaged, 10,000 unsavable." Hawke's Bay Today. Retrieved from https://www.nzherald.co.nz/hawkes-bay-today/news/article.cfm?c\_id=1503462&objectid =11020467

Wellington City Council. "Unreinforced-masonry (URM) strengthening programme." Retrieved from https://wellington.govt.nz/services/rates-and-property/earthquake-prone-buildings/unreinforced-masonry-buildin gs, accessed June 30, 2019.

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