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Resilient Homes for Pacific Rim Communities: Financial, Environmental and Health Impacts of Earthquake Damage and Improved Resilience

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ABSTRACT

Earthquakes are a frequent and devastating natural hazard around the Pacific Rim, causing significant injury and property damage, as well as loss of life. For many buildings, including our homes, there is quite rightly a primary focus on collapse avoidance and life-safety. But what is the wider impact of damaged homes on residents? This paper examines financial, environmental, and health impacts from research and the authors' experience, and considers what might be done in future to design homes that reduce the negative impacts of seismic events.

We present the current state of earthquake damage-resilient home design in the Pacific Rim region, highlighting both the challenges and opportunities for improvement. We present direct practitioner observations of major earthquake events in New Zealand in 2010-2011 and 2016 and discuss the opportunities and challenges of incorporating damage reduction design and construction into the home-build sector.

Furthermore, the paper highlights the importance of educating the public and sector stakeholders, promoting awareness of the risks to homes and how earthquake damage-resistant design and construction practices might mitigate damage to residents' finances, the environment, and health resulting from an earthquake.

The paper concludes by emphasizing the importance of collaboration between architects, engineers, builders and developers, policymakers, insurers, and communities to better protect the adverse impacts of earthquakes on the Pacific Rim housing sector.

Keywords: Resilience, homes, impacts, awareness, collaboration.

INTRODUCTION

Which building surrounds and protects us for the much of our lives? Which building contains and protects the most precious people, memories, assets, and financial value in our lives? Not usually our business or workplace. Not even our great public buildings and infrastructure. For most of us, that place is our home.

Figure 1. A typical detached home in Lincoln, New Zealand.

Over the last decade the authors have seen devastating earthquakes, extensive research into seismic risk and the performance of buildings, and the development of design techniques and construction to significantly improve both design and construction. Much of the focus of the design and construction improvements has been on larger buildings and infrastructure, and it is important to do so. However, we have observed in New Zealand and other areas around the Pacific Rim both a very significant impact of earthquakes on people's homes and some research into their performance, but very little change in construction practice. Negligible replacement, repair, and new construction has provided significant resilience improvements commensurate with the scale of impact on people, families, and residential neighbourhoods resulting from damage to low-rise homes.

Others, including David Hopkins' 2019 PCEE paper *Improving earthquake resilience of New Zealand Buildings. Who cares?* [1], have highlighted that we should all care about improving resilience, meaning buildings are safe, suffer low damage overall, and have short repair times. We have considered the opportunities and challenges which arise from seismic events, with particular focus on the mitigation of the risk of damage and repair to low-rise housing from earthquakes. We acknowledge the impact of damage that can occur in some specific soils, such as liquefaction, but that is not a primary focus of this paper.

The authors have direct experience as professional consulting structural engineers in New Zealand in the period following two large earthquakes: The Canterbury Earthquake Sequence (CES) commencing 4 September 2010, and the Kaikoura Earthquake of 14 September 2016. During that time, we inspected numerous damaged low-rise homes first-hand, met with their residents, and worked with insurers, builders, homeowners, and other stakeholders to document the damage, determine the cause (earthquake versus pre-existing), and establish earthquake repair methodologies. Many others have investigated geotechnical performance, seismology, and material performance. The research arising has informed new design standards in New Zealand and continues to do so. This paper focuses on New Zealand (where the bulk of our experience has occurred). However, we also indicate how the findings may relate more widely around the Pacific Rim, where over 80% of our planet's significant earthquake activity occurs [2].

Deloitte NZ in their 2015 report *Four years on: Insurance and the Canterbury Earthquakes* [3] note that usually it is adverse social and wellbeing consequences of earthquakes that have longer-term impacts on community psyche, even after material possessions are restored. This paper's ultimate focus is earthquake impacts on people living in and owning homes, and how to mitigate them. People are concerned with more than the performance of a building and its repair details. Their concern is the consequential impact on their lives, and those of their family and community. We have seen many examples of the impacts on people, who could be any of us living where earthquakes can happen. We have therefore considered how the stakeholders who influence the seismic resilience of homes can improve the experience of those who live in and own them.

FINANCIAL IMPACTS OF EARTHQUAKE DAMAGE ON HOME-OWNERS AND RESIDENTS

Direct Costs

The direct costs of earthquake damage on homeowners include the costs of repair or reconstruction, temporary accommodation, and potential future increases in insurance premiums. For homeowners, these costs can be considerable, and in some cases, they may exceed the value of the property. The financial burden may be exacerbated when insurance coverage is inadequate or when claims are disputed, leading to protracted legal battles and increased expenses. In February 2023, 1,000 Cantabrians were still waiting for closure from the CES 12 years prior.

Khakurel, Dhakal et al. in their 2021 paper *Residential building repair cost and claim settlement time from the Canterbury Earthquake Sequence* [4] examine repair costs from the New Zealand Earthquake Commission (EQC) database. This is a helpful assessment of the government-backed insurance portion of the total costs (In 2011, the first $115,000 of a home claim). We have yet to see research which also includes insurer and homeowner costs in order to provide the whole picture.

Determining Earthquake Damage Extent and Repair Scope

Earthquakes almost always strike without warning. In a matter of seconds, the P-waves then S-waves are felt and minds race as to what to do.

In New Zealand, the government quickly instituted a "drop-cover-hold" mindset when it became clear that aftershocks were ongoing for some. The first (7.1M_W) earthquake occurred 40km west of Christchurch city at 4:35am on 4 September 2010, a Saturday. After the immediate, awakening shock, many homeowners paused their day to assess the immediate damage themselves. They could see the damage to fallen contents, but for many the home damage was 'cosmetic' – a word that would soon become commonly used to indicate that no structural repair was needed, rather just a decorative repair. Subsequent assessments became more refined, from early rapid assessments to more detailed scoping over a period of years.

Then the aftershocks started – some 14,000 over the next 5 years [5] - with the most damaging, a nearby shallow M6.3 causing the loss of 185 lives, serious damage to much of the Christchurch CBD, and damaging over 100,000 homes in and around a city of 400,000 residents [5]. The aftershocks caused extensive delays in completing the assessment of damage, such that most homes were subject to many re-assessments, both before and after repairs were undertaken.

As time passed, engineering regulation and guidelines arising from research were altered and/or added-to. This included the MBIE (Ministry of Business, Innovation & Employment, NZ Government) Guidelines [6] first issued in December 2010 and updated four times since. Assessments and repair scopes were modified as published guidance was updated.

The combination of ongoing damaging aftershocks and new or changed repair requirements resulted in direct costs having to incorporate:

- The insurers' costs of damage re-assessment, often recurring a number of times.
- The insurers' costs for design and pricing for repair/rebuild design, often recurring a number of times.
- The insurers' costs of advisers for disputes arising from disagreement on damage and repair scope.
- The insurers' actual construction cost of the repair or rebuild.
- Some completed repairs and even rebuilds have been found to be deficient. The cost of repairs to repairs has largely been borne by insurers in the case of the CES.
- The homeowners' costs for professional advice to review and sometimes dispute the assessed damage.

Most homes in Canterbury were covered by full replacement insurance. Homeowners were therefore only covering direct costs for the repair when they were not fully insured, or when they wished to dispute the scope and cost assessed by their insurer. This level and type of insurance is an anomaly around the Pacific Rim, with homeowners in many territories being far more exposed to the financial impacts of seismic risk [7].

Repair or Reconstruction Time

The time taken to repair or reconstruct earthquake-damaged homes typically varies depending on the extent of the damage, the type of construction, and the availability of labour and materials. Before the repair or reconstruction can take place, agreement must be achieved between a homeowner and insurer. In the case of the CES, the repair time (including assessment and settlement) for a large claim (>$100,000) was approximately 3.5 years [4]. During this period, many residents were living in damaged homes, unable to fix the damage themselves, and homeowners were constrained in their ability to sell their homes. An "as-where-is" market also started with buyers offering to purchase damaged homes at a discount and address the repairs themselves.

In the case of the CES, the time taken to repair home damage was significantly impacted by the ongoing nature of the earthquakes, some causing further damage to both damaged and repaired homes. This caused the need for both re-assessment of damage, and re-design of repairs. We have not seen any specific research into these time-related costs, relative to a predominantly single-event earthquake without an extended period of damaging aftershocks.

Temporary Accommodation/Living with Damage

Temporary accommodation is often necessary for residents whose homes are uninhabitable due to earthquake damage. The costs of temporary accommodation, such as short-term rental properties or hotel rooms, can quickly accumulate, particularly if the displacement period is prolonged. Many full replacement policies included a provision for a fixed sum for temporary accommodation which might cover up to a year's rental accommodation in normal times, or a lesser period if rental accommodation demand is high and supply low, as was the case after the CES earthquake.

Insurance Premium Increases

Following an earthquake, insurance premiums for homes in the affected region increase to account for the heightened risk of future events. These increased premiums can place an additional financial burden on homeowners, particularly impacting those who are already struggling to recover from the costs associated with earthquake damage. In the decade following the CES, typical insurance costs for homes in NZ increased by 150% [8] whilst home values increased by 125% [9].

Indirect Costs

Economic Costs

The indirect costs of earthquake damage on homes includes negative impacts on local economies. In Canterbury, the CES damage repair and rebuild of homes lead to a decrease in the supply of available housing, and high demand on construction resources. The combination of effects drove up building costs, as well as rental and housing prices. Additionally, the displacement of residents resulted in lost productivity, unemployment, and increased demand for social services.

Impacts on Homeowners and Residents

The repairs and rebuilding needed to homes and businesses following the CES caused businesses to suffer a loss of customers, decreased productivity, and closures due to the inability to operate in the aftermath of an earthquake. Some 70,000 people had to leave or relocate away from the region [10]. We have not seen specific research on the cost to individuals. However, two years on, retail activity trends were still lagging the rest of New Zealand by 6%, after drops of over 40% in the immediate aftermath [11].

ENVIRONMENTAL IMPACTS OF EARTHQUAKE DAMAGE ON HOMES

Waste Generation and Disposal

Construction and Demolition Waste

The process of rebuilding 15,000 demolished homes and 10,000 demolished commercial properties after the CES generated approximately 8 million tonnes of debris [12]. However, over 100,000 additional homes were damaged and repaired with methods which often included the partial or full removal of wall and ceiling linings inside and out. We were unable to source data on the total waste created by those repairs, however a Building Research Association of New Zealand (BRANZ) Study Report from 2015 [13], based on surveying 300 homes, recorded that 55% of linings were undamaged. The remaining 45% of all linings sustained minimal to major damage at peak ground accelerations ranging from 0.2g to 0.6g. Given that not all homes required repair to all linings, the overall proportion of homes affected was between 45% and 100%. In the authors' experience of inspecting hundreds of properties, we did not inspect a single home that had no lining damage due to the earthquakes. It can therefore be reasonably assumed that there was a substantial contribution, over and above the 8 million tonnes of commercial building demolition waste, attributable to repair waste from homes. Furthermore, the comparison of lining damage with the age of the homes showed little difference between the lining damage between pre- and post-1980 construction, indicating that newer home construction techniques have made little difference to limiting damage [13].

Hazardous Materials

Amongst the physical waste were hazardous materials such as asbestos and lead-based paint. Lead and asbestos checks became a critical part of damage evaluation for most homes following the CES, revealing a common presence in materials such as asbestos/cement sheet cladding and some plaster finishes across many CES homes. The proper disposal of this waste was critical for both workers and the environment.

Furthermore, in the immediate aftermath of the 22 February 2011 earthquake, the city was enshrouded with dust arising from the damage (refer Figure 2). but in the early response phase of the event, control was very difficult apart from the use of PPE. It is yet to be seen what the effect of this initial exposure will have on the wider population present at the time of the events.

Figure 2. Gillian Needham's famous photo showing the dust cloud immediately after the earthquake of 22 February 2011.

Carbon Emissions

The repair of earthquake-damaged homes requires significant resources including raw materials, energy, and water. The extraction, processing, and transportation of these resources can result in substantial carbon emissions. Gonzalez et al [14] have quantified the embodied carbon cost from demolitions of commercial buildings following the Canterbury Earthquakes. They describe it as “staggering” in terms of both CO2 and energy. Their study covered 142 concrete buildings demolished in the Christchurch CBD. We have seen no similar research yet on emissions relating to homes damaged by the CES.

MBIE have issued a whole-of-life embodied carbon assessment technical methodology [15]. The ‘Use’ stage refers to the post-construction, pre-demolition life and provides for an assessment of embodied carbon including expected repair and replacement. A typical building life of 50 years is used, although NZ homes typically have a life of around 70 years. This methodology is not yet regulated in New Zealand as a requirement for home building but does provide a methodology which should incorporate the probability of earthquake damage to a home during its life, requiring repair, and hence the embodied carbon in the ‘Use’ phase. We look forward to seeing more research in this area to align with the research already undertaken on earthquake repairs required following the CES.

HEALTH IMPACTS OF EARTHQUAKE DAMAGE TO HOMES

Physical Health

The damage to homes and subsequent recovery caused by the CES has had significant and lasting effects on the physical health of home residents. Whilst overall there were 185 lives lost, only two of those people were in Canterbury’s 150,000 homes. Most of those homes were single or 2-storey and timber-framed with plasterboard linings. Overall collapse was very rare and so the homes did perform well in regard to the collapse avoidance objective in the New Zealand Building Code. Damage in parts of the city was caused by the settlement of liquefiable soils, and in all areas by cracking of non-structural elements but these did not cause severe physical harm in most cases.

Exposure to Hazardous Materials

During the demolition and home reconstruction process, residents and construction workers can be exposed to hazardous materials, such as asbestos and lead-based paint. Prolonged exposure to these substances can lead to severe health problems, including lung cancer, asbestosis, and lead poisoning. A 2015 study [16] advised that asbestos started to raise its head as a critical issue for residents initially but the Canterbury medical officer of health allayed those concerns in 2013. However, they also advise later in 2013 that textured ceilings with asbestos were considered a serious health risk, and processes were put in place to control the repair or removal of such ceilings. Asbestos-cement panels were also common external wall and roof soffit claddings even on homes constructed relatively recently.

Mental Health

Experiencing earthquake damage to one’s home and personal belongings can lead to significant mental health deterioration. In addition, the stress associated with ongoing aftershocks and their uncertainty was a significant contributor to stress arising from CES impacts. Apart from physical injuries, international literature suggests that psychosocial recovery after a disaster can take five to ten years [17]. A key reason for this is that a double blow often occurs. The shock and effects of the disaster itself are followed by secondary, recovery-related issues. These include dealing with damaged homes, insurance claims, poor roading and lost community facilities.

The earthquakes have impacted upon the mental health of many people. All Right? (a Canterbury District Health Board and NZ Mental Health Foundation-led initiative) has undertaken research among Cantabrians on their mental health and wellbeing. Initial research released in 2013 found that over 80% of respondents stated their lives had changed significantly since the earthquakes. Almost a third said the earthquakes had caused them financial problems, while 64% said they felt guilty that other Cantabrians were more affected by the earthquakes. Eighty-four percent gave their time to support others, nearly a third felt more connected to their neighbours, and 42% ‘a little’ connected. In 2014, 65% of city residents felt tired (a 10% increase on 2012); and 66% agreed that it felt like their life had been normal over the last 12 months, compared to 60% in 2012.

Other evidence further illustrates this impact. According to Otago University research, Cantabrians who experienced serious adversity, both through earthquake events and following consequences, were 40% more likely than those living outside the region to have at least one of several kinds of disorder including: major depression, post-traumatic stress disorder, or anxiety disorder. Rates of clinically significant nicotine dependence were 1.9 times higher in the group of people most affected by earthquakes compared to those not affected by quakes. Within this context, the divorce rate per 100,000 in Christchurch increased from 211 during 2010 to 249 in 2011, and 261 the following year. Also, “extreme concern” has been expressed among health professionals regarding increased homelessness among people with mental health issues.

A study undertaken by Kathleen Liberty [18] showed the noticeable impact of the CES on young children as they progressed through their schooling. Alarmingly, one in five children exhibited all classic symptoms of PTSD. This incidence of significant levels of PTSD was double the rate of the children surveyed before the quakes. The study concluded that exposure to prolonged stress was causing the effects, and that calming the environment for young children would be beneficial.

CURRENT STATE OF EARTHQUAKE DAMAGE-RESILIENT HOME DESIGN

Existing Techniques and Technologies

Whilst these comments largely relate to NZ stand-alone homes, many such homes of similar construction are located around the Pacific Rim, including in Japan and the west coast of Canada and USA.

In NZ, almost without exception, stand-alone homes are constructed with foundations connected or embedded into the soils beneath, with their superstructures firmly connected to the foundations. Foundations typically could include piles, a concrete foundation and/or floorslab on a hardfill base, or a suspended timber floor, all without intentional seismic isolation and/or dissipation.

One exception is the home pictured earlier in this paper (refer Figure 1), constructed in Canterbury after the CES. Whilst in all other respects very conventional in its design and construction, this home was protected by a slip layer under the concrete floorslab and seismic dissipation devices, designed to dissipate seismic energy while limiting movement to a low level in order to accommodate the building services crossing the slip surface. To-date, there have been no formal retrofitting or low-damage incentive schemes for residential homes in NZ.

In Japan, damage protection by seismic isolation/dissipation and device retrofitting is more common than in any other Pacific Rim nation, with around 7% of homes less than ten years old being built or retrofitted with such systems/devices [19]. West coast areas of Canada and the USA are yet to adopt seismic isolation/dissipation, but they are progressing well with simple robustness retrofits under incentive schemes such as the Earthquake Bolt & Brace (EBB) Scheme [20].

The superstructure above ground in New Zealand home construction would typically be framed with timber or light cold-formed steel and lined internally with a plasterboard and/or wood panel (such as plywood or composite wood board). External wall claddings could either be lightweight boards or panels or heavier systems such as brick veneer. Roofs range between lightweight steel systems to heavy tiles, with or without plywood underlay. The wall linings are often used to contribute to much of the seismic bracing.

As a consequence of the near-rigid connection between the superstructure and ground, seismic resistance provided is a direct consequence of the ground accelerations and displacements, and any inherent damping provided by the performance of materials such as nailing or screws and the elements they are connecting.

NZ uses a performance-based building code, but much housing can be constructed without specific engineering to the relatively prescriptive Standard NZS3604, deemed to meet the performance requirements. The code anticipates that homes will sustain a Serviceability Limit State (SLS, 25-year return period) earthquake without any significant damage, and an Ultimate Limit State (ULS, 500-year return period) earthquake without collapse, but with damage. BRANZ SR337 [21] found that the typical New Zealand house construction would drift to much more than 2.5% at a ULS event, far above the damage onset of such construction which sits at around 1% drift. This damage onset threshold is often also exceeded in an SLS-level event.

CHALLENGES AND OPPORTUNITIES FOR MORE RESILIENT HOMES

Lessons Learned – Impact on People

The earthquakes in New Zealand since 2010 have provided valuable insights into the performance of various residential home designs and construction practices during seismic events. More importantly, it gave insights into the impact that the damage to homes in such earthquakes can have on the people living and working in the affected areas, even though many homes were not destroyed beyond repair. Key impacts on people that we have seen in the course of providing professional engineering expertise and others have researched and written on include:

- Repair costs beyond those covered by insurers.
- The potential for increased cost of future earthquake insurance.
- The environmental impact of earthquake damage.
- The physical health risks arising from repairs.
- The very significant risk of mental health deterioration throughout the earthquake/aftershock/ repair process, and beyond.

We have seen that the CES initiated learnings related to the physical damage to homes. However, many of the impacts of the earthquakes on people and their homes have not yet been included in, or the focus of, such research. There is opportunity for further research and we understand some papers are forthcoming.

Opportunities and Challenges for Home Resilience to benefit Residents and Homeowners

The experiences in New Zealand have underscored the ability of most conventional homes to largely protect families from physical harm through structural stability, and homeowners financially with damage insurance. However, the impacts on other aspects of life were significant due to the disruption and uncertainty of damage repair. Resilience is at present focussed on collapse and the CES has highlighted a need for increased resilience to limit damage so that people can get back into their homes sooner. This limits the significant cost and distress, financially, environmentally, and emotionally that a home earthquake repair can initiate.

There is a massive opportunity to address the adverse impacts on families of damage to homes by developing, legislating, and incentivising seismic damage-resilient techniques, details, and devices. This requires the integration of the expertise of policy-makers, social scientists, and the community with that of seismic engineering experts. A co-ordinated approach can provide a significant step-change to reduce the impact of earthquakes on people by improving the aspects of resilience that impact people most significantly. These initiatives would push beyond life-safety goals and move towards truly low-damage homes.

EDUCATING THE PUBLIC AND SECTOR STAKEHOLDERS

Raising Awareness

Broad awareness of a problem to be fixed is needed to answer David Hopkins' question: Who cares? Our experience is that disaster awareness is most heightened for those who have experienced turmoil, and have done so recently. Raising awareness about the impacts on us all that are posed by earthquakes, and the benefits of damage-resistant homes in an easily-understood way is crucial to their adoption. A good analogy is the development of car seatbelts, moving from being non-existent, to optional, and now ubiquitous in our vehicles.

Beyond awareness of the issue, a willingness of leaders to engage with and support technical experts across disciplines, training programmes, and knowledge-sharing is required to help inform homeowners and residents, home builders and developers, architects, engineers, and policymakers about the latest research findings, best practices, and solutions.

CONCLUSION

Designing earthquake damage-resilient homes in the Pacific Rim is crucial to reducing adverse financial, environmental, and health impacts for all of us living in this region of frequent significant earthquakes. Whilst existing techniques and technologies have demonstrated their effectiveness in preventing collapse, there is still much room for improvement, and further research is needed to develop innovative and affordable solutions to damage resilience.

Educating the public and sector stakeholders about the risks and benefits of damage-resistant homes is essential for promoting their adoption and overcoming barriers to implementation. This will require widespread collaboration across a diverse range of expertise and stakeholders.

By investing in earthquake resilient, low-damage homes, we can not only help protect the lives and well-being of residents in the Pacific Rim but also contribute to long-term environmental sustainability and affordability of the region's housing sector.

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