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# Challenges for Earthquake Engineering Practice in Aotearoa New Zealand

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## ABSTRACT

New Zealand has experienced a decade of increased seismic activity, highlighted by the Christchurch earthquake sequence and the Kaikōura earthquake. There have been many lessons but have the learnings been adopted? In particular, it has been observed that while the life safety objectives of the building code were largely met, the levels of damage and economic impact are considered by many to be excessive.

The recent update to the National Seismic Hazard model is in the process being incorporated into the building code. This presents an ideal opportunity to consider a step change in thinking about how seismic risk is managed.

This paper will explore some of the learnings from the earthquakes. It will present and discuss recent initiatives in engineering practice that address some of the learnings and explore some of the potential changes in practice that may be implemented in the decade to come. Consideration will be given both to the design processes that may be employed and the practicalities of implementation in the wider industry.

Keywords: New Zealand Building Code, structural design practice, damage control, repairability, seismic assessment.

## INTRODUCTION

This paper sets out to give a broad perspective on where seismic engineering in New Zealand may be headed in the next decade or more, from a designer's perspective. Through looking back at a decade of 'real world' testing, New Zealand has had an ideal opportunity to re-evaluate a generation of design and building code development, overlaid by newly informed expectations from building users.

There have been many positives from the recent experiences, but there is also a sense of disappointment, partly from the 185 deaths (175 from building failure) that happened over the course of the Christchurch and Kaikōura earthquakes, but also from the significant repair bill. Most of the casualties were from buildings that were clearly not compliant with the current building code, but many modern buildings required significant repair or rebuild.

Subsequently there have been numerous changes in guidance and regulation for designers, but the most significant changes may be yet to impact. These include a significant upgrade to the National Seismic Hazard Model (NSHM) and potential changes to the New Zealand Building Code (NZBC), either directly or through the Standards that are cited as means of compliance.

This paper discusses aspects of the proposed changes which require careful consideration if New Zealand is to require different outcomes from future earthquakes in populated centers.

## BACKGROUND

### The New Zealand Building Code

The Napier earthquake of February 3, 1931, sparked the early development of seismic design in New Zealand. Since then, and in parallel with other seismically active countries, New Zealand has evolved its design techniques and building code to its current state.

The current New Zealand Building Code (NZBC) [1] is broadly performance based, with high level objectives of Section B1, Structure being to:

a) Safeguard people from injury
b) Safeguard people from loss of amenity
c) Protect adjacent property

The objectives map to specific performance objectives which are normally deemed to have been satisfied by designers using the suite of cited standards, including the loadings standard and the materials standards.

The NZBC is administered by the Ministry of Business Innovation and Employment (MBIE) both directly (through the Building System Performance team) and through Standards New Zealand (SNZ), SNZ is an independent business unit within MBIE, responsible for the stewardship of the loadings and material design standards that are generally used to ensure compliance with the NZBC. In addition, MBIE plays a role in the occupational regulation of structural engineers who apply the NZBC.

### Context – the Built Environment in 2010

New Zealand's cities have largely been developed since the mid-1800's. Early construction typically used freely available local materials, mainly wood, but often unreinforced masonry for some of the more substantial buildings. As local industries developed, stone masonry gave way to brick and most of the cities and regional town centers had a significant stock of brick buildings. Unreinforced masonry was largely abandoned for new construction following the Napier earthquake of 1931, but the rudimentary seismic design that was practiced from that time through to the mid-60's left a considerable legacy of non-ductile structures.

The mid-60's saw the introduction of more deliberate seismic design provisions, but it was not until the mid-70's, with the introduction of capacity design principles, that designers started to consider the performance of buildings through a wider spectrum of possible earthquake shaking, consciously or otherwise. A fundamental tenet of capacity design was understood to be that buildings may be irreparably damaged in a severe earthquake, but would have sufficient toughness to resist collapse through long-duration shaking of high amplitude. This understanding was, arguably, limited to the engineering profession.

New Zealand experienced a period of rapid growth and redevelopment of its major city centers through the 80's. This construction boom led to innovations in building techniques as builders sought ways to compete for resources and materials. Structural steel was regarded as expensive and potentially difficult (due to labor union issues as a result of the BNZ development in Wellington). Consequently, New Zealand became a 'concrete country' with common use (arguably, overuse) of precast concrete to minimize site labor demands. This became even more engrained with the resulting gradual loss of on-site formwork construction skills.

Almost all buildings of this era used precast flooring systems, typically extruded 200mm or 300mm hollowcore planks with a thin (65-75mm) reinforced concrete topping. Quick and easy to use, these systems were prevalent until the introduction of steel composite flooring started to make inroads as an alternative, in the 90's. Doubts about the performance of precast flooring in earthquakes had surfaced following the Northridge earthquake [2-3]. This led to improved design processes in successive code updates, but the majority of new construction in 2010 probably still used precast flooring systems.

An associated issue was the use of non-ductile hard-drawn wire mesh to reinforce topping slabs and steel composite decking. Research into the performance of precast flooring had also highlighted the need for ductile reinforcement in elements where it had previously been considered adequate simply to supply strength but wire mesh continued to be used through to the mid-2000's.

Although the trade union issues were a thing of the past by the mid-90's, structural steel continued to be restricted largely to industrial structures, for cost reasons. Local steel production was limited to plate and small hot-rolled sections and a combination of exchange rates and high international demand made it often too commercially risky for large buildings to be designed in steel.

In 2010, the construction industry was slowing, reflecting the global downturn of the GFC. The largest cities had undergone varying degrees of urban renewal over the previous 40 years and were a broad mixture of 2-3 level unreinforced masonry buildings, mid-rise ductile and non-ductile concrete buildings, with some taller ductile steel and concrete buildings. There was limited used of base isolation (almost exclusively on public and heritage buildings) and some emerging use of new technology, such as PRESSS frames and the forerunners of mass timber construction as we think of it now.

## THE EARTHQUAKES

After a long period of seismic quiescence, New Zealand experienced an unprecedented series of seismic events in the last decade. These events have tested for the first time the basis (at least) of the current building code, which dates back to the mid-70's and the introduction of capacity design. The most significant events were the Canterbury Earthquake series and the Kaikoura earthquake.

**Canterbury Earthquakes, 2010-2012**

The Canterbury earthquake series commenced in September 2010, with the most damaging event being the Mw6.2 Christchurch earthquake of February 22nd, 2011. There were 185 deaths, 3,129 injured [4] and it is estimated that the rebuild costs ran to NZ$40B, split approximately:

- $16B commercial construction
- $16B residential construction
- $7B infrastructure.

The Feb 22nd earthquake was notable for the very high intensity of shaking over much of the city. Although the magnitude was relatively small (compared to Kaikoura), the earthquake was shallow and scored a 'direct hit', with the majority of the CBD being within 10km of the epicenter. Many records showed shaking levels well in excess of the design standard of the day, although only for a short duration. There was widespread liquefaction, affecting parts of the CBD, but having the greatest impact on residential areas in some riverside or seaside suburbs. However, residential buildings performed well in those areas where there was no significant liquefaction, with mainly cosmetic damage. The exception to this was in some of the hillside suburbs, where there were issues with landslides and rock roll and where architecturally designed homes that had been designed with open faces to take advantage of the expansive views proved to be unsurprisingly vulnerable to high accelerations near the epicenter.

The performance of buildings in the CBD was mixed. Two buildings (PGC and CTV) accounted for the majority of lives lost. Neither could be regarded as code compliant, although the CTV building design was recent enough that it should have been. Arguably, there were several more modern era buildings that may have been near collapse if the high intensity shaking had persisted for longer. Many of these were subsequently demolished.

Liquefaction had significant impact on building damage – many buildings that performed adequately from a life safety perspective were deemed irreparably damaged due to liquefaction and lateral spread, leading to significant structural deformation. On the other hand, some such buildings were remediated with the deformation 'locked in', notably the Christchurch Town Hall, with up to 250mm of differential settlement around the main auditorium, successfully accommodated within the reinstatement program.

A case study of 223 CBD buildings [5] revealed that 62% were demolished within five years of the earthquake, with the fate of a further 9% still in the balance at that time. Even now, there are buildings for which no final decision has been made, or which are still in dispute with insurers.

There was a complex series of drivers behind these decisions, not least of which was the unusually high level of earthquake insurance in New Zealand. Swiss Re [6] estimated 80% of the repair cost was paid by insurance. This is almost the inverse of similar events at around that time in for example Mexico, Chile or Japan.

The Ministry of Business, Innovation and Employment (MBIE) Seismic Risk Working Group (SRWG) (November 2020) [7] evaluated the performance of Christchurch CBD buildings as part of an investigation into seismic risk and building regulation. The SRWG's conclusions about actual building performance relative to the code performance objectives could be summarized as:

- Modern code-compliant building generally met the life safety objective of the code although there were significant potential life safety issues with non-structural elements and more particularly, contents, such as racking.
- Performance against the amenity objectives was generally disappointing, although this is much more subjective to assess:
  - The levels of damage to primary structure were probably greater than expected, and the widespread extent of the damage coupled with limited access and availability of resources made the reoccupation process slow. This was compounded in many cases where otherwise usable buildings had access limited due to the proximity of precariously damaged structures requiring stabilization or demolition.
  - Non-structural damage was widespread, having had little attention over the years.
  - Repair often proved more difficult than had been expected, particularly with the combination of precast floor and ductile concrete moment frames. Often, even relatively modest repairs to the primary structure resulted in complete strip-out of the building.
  - Liquefaction was often a determining factor – buildings with little or no settlement were able to return to operation quickly but those with significant settlement were often not.
  - Insurance had a significant role, with owners in some cases delaying reoccupation of otherwise usable buildings pending insurance resolution, which was seldom quick (common across all building types, but possibly more prevalent in industrial facilities with lower amenity needs).

**Canterbury Earthquakes Royal Commission**

In light of the number of deaths and the levels of destruction following the earthquakes, a Royal Commission was called, tasked with investigating performance of buildings in the Christchurch CBD and the adequacy of the legal and best-practice requirements for design, construction and maintenance of buildings in the CBDs of New Zealand. The final CERC report was published in December 2012[8]. In total the Royal Commission made 189 recommendations, the vast majority of which became the responsibility of MBIE to deliver. These recommendations have formed the basis of a substantial work program for MBIE, for the last 10 years.

**Kaikoura Earthquake, 2016**

The Mw7.8 Kaikōura earthquake of November 14, 2016 caused less damage overall, due to its more remote epicenter (relative to larger urban centers), although the complex fault rupture sequence focused considerable energy on Wellington. There was considerable disruption due to damage to the coastal road north of Kaikoura township, which remained substantially closed for a period of 13 months and cost in the region of $1.24B to repair. This was a graphic illustration of the need for redundancy in critical infrastructure, with the alternative routes north of Christchurch having limited capacity to deal with the increased volumes of freight and general traffic. This remains an issue in many parts of the country.

The impact of the Kaikoura earthquake in Wellington was much more focused, through a combination of the unusual nature of the earthquake fault rupture sequence and the local geology and topography. The earthquake occurred over a surface rupture array of at least 21 faults [9] commencing near Culverden (95km north of Christchurch) and culminating on the Needles fault, approximately 180 km further northeast and only about 60km from central Wellington. Wellington itself is a natural harbor with reclamation over shallow alluvial deposits around much of the foreshore, overlying two main rock basins, the Thorndon basin and the Te Aro basin. A significant portion of the CBD spreads over these basins, with further development extending up the surrounding hills.

A significant outcome of these factors was that while reference sites on the rock in the surrounding hills experienced relatively low levels of shaking and little damage, there was significant amplification of shaking in the period range of 1 to 3 seconds. Bradley (2017) [10] reported peak amplifications in the order of 4 times the rock reference sites and well in excess of the code 500 year return period shaking for such sites around the CBD.

Several buildings were immediately reported as severely damaged, and as many as 8 buildings were demolished soon after the event. One building on the foreshore, Statistics House, lost support for three precast flooring units which fell to the floor below, over two floors. The Ministry of Business, Innovation and Employment commissioned an independent expert review to determine the root causes of the failure and identify implications for the building regulatory system. An early outcome from this process in turn triggered a wider review of existing buildings with the following characteristics:

- Precast flooring systems and principal lateral load resistance through concrete moment frame action
- A natural period in the range of 1-2 seconds (equating to a height range of 8-15 storeys, but as low as 6 storeys for very flexible buildings)
- Situated in areas prone to amplification in this period range, due to basin effects or soft soils.

The basis of these criteria was a suspected vulnerability to loss of seating of precast flooring systems.

The resulting 'Targeted Damage Evaluation" provided a detailed snapshot of what could be a pointer to future building damage in Wellington. From a building performance perspective, most interest centered on the Wellington CBD, notably the Te Aro and Thorndon basins. A report prepared for the Wellington City Council [11] showed that, of a total of 72 potentially vulnerable buildings, 9 were significantly damaged, leading to demolition, and approximately 50% had either no structural damage identified, or no damage that could be attributed to the earthquake.

A notable outcome of the Kaikoura earthquake was that there was little damage to the considerable stock of unreinforced masonry buildings, many of which are clustered on the edge of the Te Aro basin. The reasons for this were clear to structural engineers but after decades of public education on the risk of UMBs, the apparent contradiction of this against the levels of damage to some considerably newer engineered structures did little for the public's confidence in structural engineers.

Similar to Christchurch, there are still outstanding insurance claims and empty buildings around Wellington. Another flow-on effect has been 'inflation' of strengthening targets for buildings, with many large tenants adopting minimum capacity policies in their leasing requirements.

**Public Expectations**

Nothing focusses attention on earthquakes as effectively as earthquakes. Prior to the Christchurch events, there was almost certainly a degree of complacency over much of the country. In the period since that and the Kaikoura earthquake, public consciousness has certainly been lifted. A positive outcome of this was the success of the Wellington Unreinforced Masonry

Strengthening Program, in which there was enough political will generated after the Kaikoura earthquake to pass local mandates resulting in the seismic securing of the facades and parapets of 113 unreinforced masonry buildings over approximately two years – despite there being little damage to these buildings. This was something that had not been managed in the previous 30+ years of often ignored regulation and enforcement.

Another by-product of public attention is a growing awareness of the potential shortcomings of the building code when it comes to minimizing damage. This has never been any secret among engineers – however common knowledge among the design profession has never translated to public awareness. The level of damage and consequential demolition and repair were a shock to many, particularly from the Christchurch events. But also from the Kaikoura event in Wellington where relief at the lack of significant damage to unreinforced masonry buildings was secondary to shock at the extent of damage to relatively modern buildings – all explainable by engineers but counter-intuitive to the general public.

The New Zealand earthquake commission (EQC) has funded a recent (progressing) study into societal expectations. The Resilient Buildings project was conceived with the objective of understanding how societal expectations have changed, and how this may inform future code development.

Key findings from this research include:

- While life safety is paramount, the current building code provisions appear reasonably effective in delivering acceptable (or at least not intolerable) outcomes. But noting that this has not yet been tested in an extreme event, for which we are relying on capacity design and ductile detailing to see us through.
- Conversely, expectations for damage and loss of functionality are not being met and the Resilient Buildings group[12] estimates there is an 'order of magnitude' gap between expectations and performance.
- It is apparent that there have been significant shifts in the way we occupy and use buildings in the time since our current code was conceived.

## THE NEW ZEALAND BUILDING CODE – WHERE TO NEXT?

### Seismic Hazard Review

Following the CERC report and recommendations, the Institute of Geological & Nuclear Science (GNS) was commissioned to undertake a complete review and update of the National Seismic Hazard Model (NSHM). This has been the first major review in over 20 years and in a similar pattern to other countries' reviews, such as in North America over the last decade or so, has resulted in a significant increase in the estimation of hazard over much of the country. Some of the more seismically active parts of the country have seen increases in the order of twice the pervious hazard model, depending on building period range and sub-soil conditions. Some of this has resulted from greater understanding and ability to model the geological context – in particular the modelling of the Hikurangi subduction zone that runs the length of the East Coast of the North Island. There has also been significant development of the ground motion models, including ongoing research into the presence and effect of basins that underly some of New Zealand's main centers.

The new NSHM was formally released in October 2022. This was not unexpected, but has preceded the publication of an updated seismic loadings standard, ie the means by which it may be practically applied. The dilemma of whether to publish the NSHM first and risk the confusion of having a gap in the knowledge of how to apply it, was resolved in favor of having the data accessible for those that needed it, including interests outside the design fraternity.

Following the publication of the NSHM, MBIE announced a Seismic Risk Work Program, intended to implement the findings of the NSHM into the building controls system.

### Seismic Risk Working Group

In anticipation of the publication of the NSHM, MBIE had already assembled the Seismic Risk Working Group, tasked initially with reviewing the building controls system and identifying opportunities for improvement. This work then transitioned into a staged project to implement some of the identified improvements. Stage 1 was focused primarily on ensuring the life safety objective of the NZBC is met. This has been a relatively simple and limited scope project to incorporate the new NSHM into the earthquake loadings standard, along with some other minor recommended revisions.

Stage 2 is focused more on the amenity objective of the NZBC and in achieving consistency of outcomes. The immediate goal is to put forward recommendations for a more comprehensive set of changes, which may be more far reaching.

Some Stage 2 SRWG considerations include:

- The performance objectives and functional requirements of the building code, in particular with reference to changing societal expectations of building performance in earthquakes
- The limit states defined in the loadings standard and whether they are appropriate to deliver the expected performance.
- The design approach that is adopted in meeting the limit states
- The provisions relating to aspects such as regularity, redundancy and reliability, in reflection of the impact they have on building performance.

The SRWG is currently poised between Stage 1 and 2. A draft Technical Standard (TS1170.5) has been delivered and after further review in the Standards NZ system, should go out for consultation in the coming months. This may then be used alongside the current loadings standard as an 'alternative solution', recognizing that it cannot be immediately cited under the building code. Subject to the outcomes of Stage 2 of the SRWG activity, TS1170.5 may be amended considerably before final publication and citing into the building code.

Stage 2 will address much of what follows in this paper.

## POSSIBLE DIRECTIONS FOR DESIGN

### Performance and Limit States

Noting the findings of the Resilient Buildings Study Group, among others, there is clearly a need to review the question of whether the current life safety emphasis is sufficient in the modern context (noting that the existing NZBC amenity objectives do not typically drive the design).

One simple measure for building performance in earthquakes may be damage, which is most conveniently expressed as a damage ratio, typically presented as a ratio of the cost of the damage/repair to the total value of the building, with 100% representing collapse. A hypothetical distribution of this is illustrated below in Figure 1, noting that this is prepared from judgment and experience, not exhaustive analysis. The accompanying Figure 2 considers a cross-section of the overall distribution at a fixed damage level (in this case, 50%), prepared on the same basis.

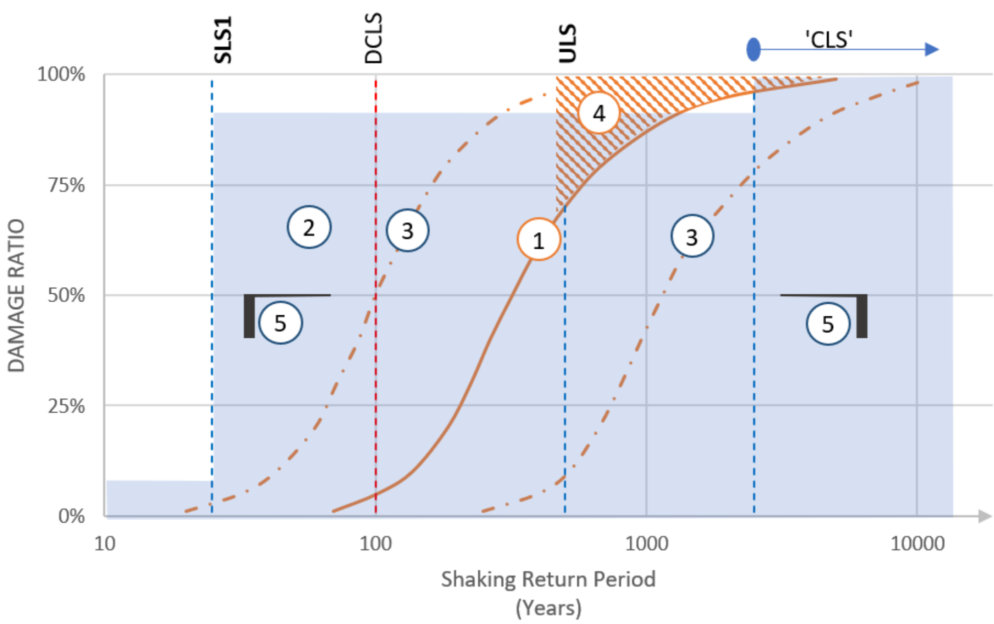


*Figure 1: Representative Damage Ratio vs Shaking return period, for all buildings.*

Notes:

1. The solid line is an estimate of the median damage ratios for all buildings
2. The blue shading is a representation of the minimum acceptable performance as currently defined by the loadings standard NZS1170.5, for normal buildings. That assumes that the most significant life safety risk is represented by collapse.
3. The dotted lines are representative of the distribution of the outcomes – notionally, the 10% and 90%iles.
4. The diagonal shaded area represents the 'insurance effect' (although not necessarily limited to insurance). That is, when the damage ratio reaches a high enough level, the building is written off.
5. Cross-section of the distribution – see Figure 2 below.

A key point illustrated in Figure 1 is the implied tolerance for high levels of damage in relatively low intensity earthquake shaking. This comes about because the of the large gap between the SLS1 and ULS design points (for most buildings). SLS1 is the serviceability state intended to test amenity, measured as little or no damage in frequently occurring earthquake shaking levels. The exception to this is Importance Level 4 buildings (typically, essential facilities such as hospital emergency centers) which have an additional design objective of being able to deliver essential services in a post-disaster situation, with some reduced functionality accepted.

ULS is generally accepted as a life safety protection measure, noting that in reality, this is not a single identifiable point in the buildings performance as the ULS condition may be reached once a mechanism is fully formed, but should then persist as the shaking intensity increases. This is also an issue when characterising damage, as simply reaching a ULS condition may not result in demolition being required, but buildings continue to deteriorate through successive cycles of load.

As described above, New Zealand has relied heavily on capacity design and ductility to ensure good life safety performance. These principles are well established and generally understood, but have some shortcomings. In particular, the misconception that ductility is used simply to reduce the design loading to a manageable level. That is potentially dangerous if designers do not consider the other important aspects of capacity design. Often, designers can select a high design ductility, but then neglect to verify it is achievable. Displacement compatibility with secondary structure and non-structural elements can be neglected and irregularity is simply compensated for by designing for a slightly higher load – which does not suppress the associated poor behaviour, it simply delays it, sometimes.

Perhaps the most significant issue, which may contribute to the unexpectedly high levels of damage, is that a building designed for high ductility may reach its yield drift at demand levels not far above the SLS1 level – hence the blue shaded area in Figure 1.

Conversely, buildings which are designed for low ductility demand ($\mu$=1 or 1.25 at ULS), may not perform as well when the shaking intensity is much higher than the design level, s the formation of reliable mechanisms is not always assured.

A possible solution for this is to introduce a new limit state for all buildings (eg Damage Control Limit State, DCLS, as indicated on the figures). This could be used to switch the controlling design criteria from life safety/ULS to other measures which may include damage limitation, functionality and repairability – all aspects of amenity – but at a level that may control the design, unlike SLS1 as currently used.

**Damage Control Limit State – how might that work?**

The SRWG is likely to test this option. Further development of the concept is required, but in principle, it could follow a process as follows:

1. Design structures to a limiting drift at DCLS that will suppress damage to non-structural and secondary structural elements. This would be limited to essentially elastic demand, ie ductility in the range $\mu$=1 to 1.25. The limiting drift may possibly be selected by the designer, but is likely to default to a value or values reflecting light damage states only (DS-1) for common building elements such as wall linings.
2. Complete a capacity design process to ensure that only acceptable failure mechanisms may form as the building reaches the ULS condition. Note that capacity design is independent of load input, ie it does not matter that a ULS design process has not preceded this.
3. Detail potential yielding elements and other key elements for 'full ductility' to ensure reliable behaviour as the structure develops a full mechanism and approaches collapse.

This could be summarised as 'design for drift at a level that matters and add ductility for anything more'. Among other benefits, this would alleviate the inevitable recurring debate on force reduction or ductility factors for buildings.

There are a few aspects to this that need consideration:

1. There are some forms of structure for which capacity design is not practically possible, for example large low-rise performance spaces or gymnasiums, or big box retail centres. These may still be governed by ULS design, or alternatively, there may be some relaxation of the need for full capacity design if certain strength requirements can be met and provided that elemental capacity design is achieved, for example through controlled yielding of the right components in connections.
2. It is possible that a ULS design condition may still govern more generally in some areas of low seismicity, where the difference between the DCLS and the 'MCE' (to use the North American terminology, not widely used in New Zealand) is too great. This may be resolved by artificially increasing the DCLS level so that the DCLS/MCE ratio is similar to more seismically active areas, or by retaining the ULS design procedures in parallel.

3. All of the material standards in New Zealand are currently written for a ULS context. Significant review may be required, but this may not be as daunting as it sounds. The existing capacity design and ductility provisions need not change and limiting material strain limits, rotations etc should be similar, although possibly modified for repairability. In fact, it may be possible to simplify these standards, which would be generally beneficial.

**Matters Other Than Design Limit States**

It is important to consider that a full system level review should include much wider consideration of the factors leading to good (or adequate) performance. It is often observed that buildings typically fail for reasons other than inadequate design loading. Such factors include:

- Missing or highly convoluted load paths
- Irregularity
- Lack of redundancy
- Poor siting
- Poor construction and maintenance.

The corollary to this is that any improvements to the building code by changing demand levels or limit states may not be effective if these other issues are not also addressed.

In this light, it is of interest to consider also the distribution of performance within a given damage ratio – eg 50%, as the section marks in Figure 1 indicate. This is illustrated in Figure 2 below, prepared on the same basis as Figure 1, ie liberal engineering judgement. The heavy line represents the distribution for all buildings, while the other lines represent individual subpopulations of distinct building types that make up the population – without being specific and noting that there is a much wider degree of variation possible.

The distributions of both the overall population and the individual building types may be even more skewed than represented below. It is possible that the upper end performance is better, but the lower end tail could be more compressed or curtailed, particularly at lower damage ratios, when all buildings should at least meet the SLS1 criteria. It is possible, as implied in the diagram, that some of the populations of code compliant buildings could incur high levels of damage at demand levels only slightly above the SLS1 earthquake shaking level. For example, for buildings on shallow foundations, sited on land that is prone to liquefaction at shaking levels only slightly above SLS1, something that is relatively common.

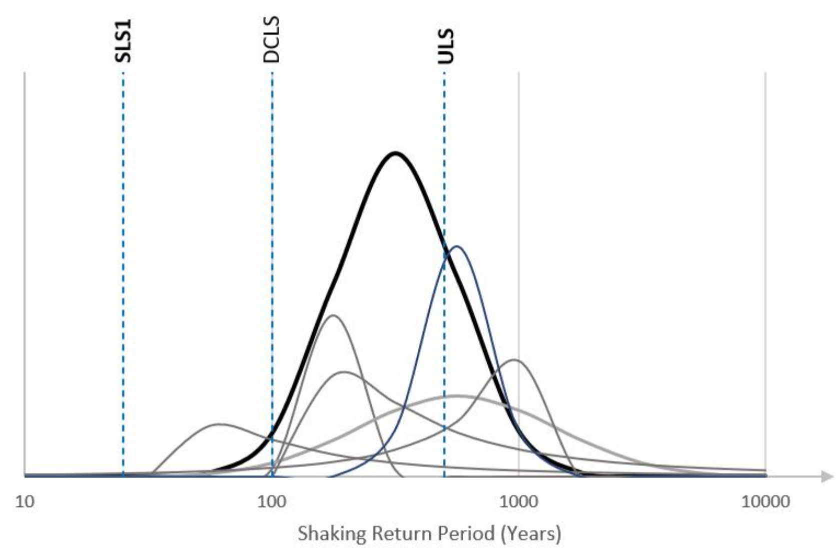


*Figure 2: Example distribution of 50% damage ratio against shaking return period*

With reference to Figure 2, one of the most important points this illustrates is that all building types do not perform equally, regardless of being designed for notionally the same level of demand. Noting this, and considering the full breadth of the building controls system, possible actions to improve performance include:

1. Curtailing the lower end and/or shifting the entire distribution by applying tighter controls and limitations on land use and site selection. Not a structural engineering response.
2. Curtail the lower end of the distribution through better execution and compliance, putting more effort into weeding out the non-conforming buildings before they are built. Note this recognizes that the distributions above include a proportion of non-conforming buildings that pass through the system undetected and are likely to be the poorest performers (as often observed). Not a structural engineering response.
3. Shift the entire distribution through increasing demand at the design points, with the existing design methodologies and practices otherwise unchanged.
4. Shift the lower end of the distribution through imposing greater limitations on existing design methods – eg tightening regularity, redundancy and drift provisions.
5. Remove or modify the behaviour of some of the lower end subpopulations. Not a structural engineering response.
6. Change the performance objectives and design points to give more reliable outcomes by potentially changing the shape of the damage ratio distribution – steeper and further to the right. This would most likely involve a change to the shape of the blue shaded 'minimum acceptable' performance envelope.
7. Employ design measures which limit the impact of damage to the primary structure on the other secondary structural and non-structural elements. This should reduce the damage ratio for a given intensity of shaking.

The optimum answer could include all of the above, but it is important to recognise that this is a system-level review, which includes consideration of a wider range of variables than simply what is contained in the building code. Approximately half of these potential controls are not structural engineering responses (as noted where relevant). A related issue is that changing one part of the system only may not make any change at all to the outcomes – an important point for the profession and regulator to consider as we approach significant increases in design seismic demand.

**What when the damage happens?**

Regardless of all the measures that may be taken to delay the onset of damage or reduce its extent, a severe enough earthquake will still cause damage. A significant learning experience from the earthquakes in New Zealand was that we were not well equipped for the assessment and repair phases. New Zealand has unusually high levels of earthquake insurance, but this placed even more pressure on the industry to address this and there are still numerous disputes from those events.

A significant consideration for the future is how we might factor in designing for repairability and ensuring that we have the means to assess and devise effective repairs. Among the issues that arise are:

1. Determining what levels of damage are repairable. This was particularly vexatious during insurance negotiations in consideration of cracking to concrete, and the impact on reinforcement. Arguments were advanced that epoxy is not a suitable repair technique as it does not restore stiffness, which was seen as part of the 'as when new' insurance policy response. This led to the question of what stiffness is being discussed, noting the design assumption of reduced stiffness to allow for cracking, in ductile buildings. The reinforcement debate centered on the impact of strain hardening – on the one hand a positive attribute as it drives the formation of further cracks, but a potential problem in the event of multiple cycles of yield at one location. In some cases, reinforcement necking or full fracture was reported in key locations.

2. Accessibility for repair. It is a general observation that while structure may account for only 20-25% of the value of a building, repair often required a full strip-out in order to access and implement the repairs. This led to many buildings being written off as the other 75% of the value was lost before any structural repairs could be implemented.

   With more use of alternative systems (added damping, sacrificial elements), there is potentially a gradual move away from mechanisms which result in damage to the primary gravity load carrying elements of the building. This may be an opportunity to think differently about design, where sacrificial elements may be used that may need replacement after a severe earthquake, but the replacement could potentially be done without decommissioning the building. However, architects will need to accept that these elements need to be placed where they can easily be accessed, for example not at the back of the elevator shaft.

A significant related question is whether it is reasonable for repairability to become incorporated into the NZBC, which is intended to set <u>minimum</u> acceptable standards for building design; or should remain a design choice for owners and designers to consider. The desire for this to be codified is surmised from the Resilient Buildings report, but has yet to be assessed with a Cost-benefit study.

### Sustainability as a Driver for Increased Performance

In addition to their Seismic Risk Work Program, MBIE is working in parallel on a Building for Climate Change Program, as part of a wider governmental commitment to meeting the Paris Agreement. The overall objective is to reach net zero emissions for the country as a whole by 2050. It is yet to be announced what targets this will translate to for the construction industry, but dramatic improvement is required.

There is potentially a dilemma here – how to balance the desire to build more robustly against the need to reduce emissions, recognizing that the construction industry is responsible for a significant proportion of emissions (approximately 20%) in New Zealand [13]. On one hand, there is a clear imperative for new buildings to be as operationally efficient as possible, and achieve as long a life as possible. On the other hand, that achieving a long life may require more robust construction (driving a higher carbon footprint) for events that may not happen over a building's lifespan, but noting that better performance does not necessarily mean more structure.

## EXISTING BUILDINGS – WHAT TO DO WITH OUR BUILT LEGACY?

### Seismic Assessment

New Zealand is unusual in having a numerical assessment process for all or most existing buildings. Buildings are assessed against the minimum standard for equivalent new buildings and given a seismic rating (expressed as XX%NBS, or alternatively, given an alphabetical grade applied to bands of %NBS ratings). The assessments may be qualitative (an Initial Seismic Assessment or ISA) or quantitative (a detailed seismic assessment or DSA). The terminology is perhaps misleading – many assume that an ISA is not of much value and a DSA is required for all buildings. This is not necessarily correct, much of the time.

The methodology for this assessment process was originally developed by the NZ Society for Earthquake Engineering and has most recently been updated by a wider group including representatives of the Structural Engineering Society and the NZ Geotechnical Society in 2017, to coincide with changes to the Building Act. It has been adopted by MBIE (who have part-funded its development) as a means of assessing whether buildings are earthquake prone as defined in the Act (ie have seismic capacity less than 34%NBS and which, if they failed, could cause hazard to human life).

Beyond simply providing an assessment methodology to determine whether a building is earthquake prone, the seismic ratings have been adapted for a variety of other purposes. Prospective tenants of buildings may search based on ratings, real estate agents market buildings for sale or lease according to ratings, building owners commission seismic upgrades to achieve certain level of rating improvements. This is not to say that the ratings are well understood. They assess only life safety performance and have little relevance in determining potential damage and loss outcomes. Although a rating of 100%NBS implies performance as good as a new building, the reality of the rating system is that a new building should achieve a rating of 150%NBS at least (although scores over 100%NBS should theoretically not be given).

A further significant compounding effect is the Health and Safety at Work Act (HSWA). Although Worksafe has issued a statement saying that building owners and tenants that are managing risk in accordance with the Building Act will not face prosecution in the event of buildings failing in earthquakes, the legal profession is arguing that the HSWA puts a greater onus on building owners, business owners and boards to adopt higher levels of seismic safety than 34%NBS (ie not earthquake prone) would deliver.

With the revisions to the NSHM, we have a significant dilemma – should we revise existing ratings down (or potentially up, in some cases) to reflect the increased hazard knowledge, or leave the existing ratings as they are? The former represents a significant penalty on many owners of existing buildings, particularly those that have invested in improvements, some of whom could potentially be in the position of having upgraded their buildings to comply with the earthquake prone building regulations, only to have to do it all over again if their building was reassessed as <34%NBS against the new NSHM.

The Building Act anticipates this, to a degree. Legally, the assessments are to be against the building code as it stood at the date of enactment in April 2017. However, this is limited to the definition of earthquake prone. The wider industry is aware of the NSHM and is poised on jumping to assessments against the new NSHM – without necessarily considering all the ramifications.

Another potential challenge is that if the performance objectives of the building code are amended to be more focused on damage avoidance and functionality, the relativity of the assessment process becomes less relevant. This invites review of the terminology and a greater separation of assessment from design. Most notably, if the design of new buildings becomes focused on damage limitation and repair, it will no longer be appropriate to have a measure for existing buildings expressed in relative terms to new buildings. Arguably, this would be a good outcome in itself, as the current process has led to perverse outcomes.

Among the shortcomings of a highly numerically based assessment process is that it does not necessarily highlight the most critical vulnerabilities of a building when viewed in the context of all possible levels of shaking. While, philosophically, both new building design and existing building assessment use design points to address performance over a full range of seismic demands (eg ULS load criteria), the relationships between the design points and greater demands are not necessarily assured in the same way. This is a potential trap for buildings being assessed or upgraded against targets lower than 100%NBS in particular. The vulnerabilities identified to have capacity less than the target and therefore to be upgraded to just above it, may have much lesser consequence of failure than elements not addressed because they are just above the target.

A further issue that is not widely understood is that often the improvements that result will do little to improve other aspects of performance, particularly damage and functionality. In other words, they may save lives but not buildings. While life safety is important, the absolute level of life safety risk is much lower than many other activities, for example driving. This was recently highlighted in published guidance for building owners [14].

This author contends that, as a country, we are spending far too much money on detailed assessment, chasing more precise estimations of risk. We would be better served by simply making buildings perform better, with lower consequence of failure, which could be achieved through simple qualitative assessment and methodical elimination or mitigation of the most significant vulnerabilities, the failures of which may lead to the worst outcomes. This is not a new concept – it mirrors the ordinance approach widely used in the US, for example.

**Sustainability Overlay**

Once again, sustainability becomes a significant overlay for these considerations. Analysis suggests that more than 50% of the embodied carbon in New Zealand building construction [15] comes from the superstructure and foundations. It is clear that if buildings can be effectively repurposed with an appropriate level of seismic upgrade, significant reductions in embodied carbon can be achieved and the collateral benefit in less impact of waste disposal on landfill. In return, a possible compromise in levels of seismic safety seems a small price to pay.

The challenge here is to get the broader public to understand and agree that the tradeoff of slightly increased seismic risk is worth the significant reduction in environmental impact.

## CONCLUSIONS

The implementation of the new National Seismic Hazard Model into the New Zealand Building Code offers a 'once in a generation' opportunity to make significant and meaningful changes to the way New Zealand building designers approach their work. At the same time, both new building design and existing building assessment also require careful re-evaluation in light of New Zealand's commitments to reduce carbon emissions (and more broadly to improve sustainability across the industry).

**New Building Design**

Assuming the public expectation for reduced levels of building damage in moderate to severe earthquakes is maintained, it seems intuitively simple that building design should shift from focus on a life safety (ULS), to design points that directly address damage at levels of shaking that better reflect the public expectation. The Damage Control Limit State and design process outlined in this paper requires considerable further consideration, but appear to address this, in principle. They may also have the benefit of simplifying aspects of design in New Zealand that are currently perhaps unnecessarily complex, for little actual gain.

In parallel, a wider system review is desirable, to ensure that the proposed changes have the desired effect.

This could be the most significant change to seismic design in New Zealand in the last 50 years, which will be challenging for the profession to implement. The transition will need careful planning, through communication and training of the profession, to more detailed review of the material design standards that follow the loadings standard.

Not least among the challenges will be negotiating the political landscape, where the public (or their representatives) will need convincing that this can be achieved at reasonable cost with minimal disruption. However, the improved performance of the building population in similar events to the Canterbury and Kaikoura earthquakes should justify this.

The reward for getting this right will be a transition over time to a building stock that is more resilient and would be expected to suffer considerably less damage in the event of earthquakes such as those experienced over the last decade.

**Existing building evaluation**

There has been a 'virtuous spiral' of increasing expectation of the seismic safety of existing buildings in recent years, fueled arguably by a misunderstanding of the risk that most existing buildings present. This has resulted in disproportionate levels of seismic assessment and upgrading expenditure, not necessarily resulting in the improvement in performance that many expect.

Arguably, a resetting of expectations is required, which may be enabled by unlinking seismic assessment ratings from relativity to new buildings. It is implicit in this that the public in general accept that a lower level of seismic safety from older existing buildings, provided that the worst vulnerabilities of those buildings are identified and mitigated. Simpler assessment and improvement methodologies would allow investment to be streamed to either repair, or better still, improvements in the resilience of new buildings, where much greater return from investment is expected.

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