

A. The Christchurch Women’s Hospital was the first base-isolated building in the South Island, opened in 2005. The lead rubber bearings located at the underside of the lower ground floor add flexibility to the building, giving a more gentle rolling motion during a major earthquake (source: Andrew Charleson)

B. The Alan MacDiarmid building constructed in 2009 was the first Precast Seismic Structural Systems (PRESSS) building in New Zealand. It has internal post-tensioned tendons clamping prefabricated concrete elements together. The beam-column joint shown rocks in a large earthquake with the external steel elements acting as a means of energy dissipation (source: Alistair Cattanach)

C. The Te Puni Student Village buildings are steel structures that incorporate the sliding hinge joint as shown. Clamped plates at the bottom of the beam slide with friction to suppress damage to structural members (source: Sean Gledhill)

D. The Nelson Marlborough Institute of Technology building is shown under construction in 2010. It uses the latest Pres-Lam technology developed at the University of Canterbury. Rocking timber walls are post-tensioned to the foundations and are coupled using U-shaped flexural steel plates. All structural elements are constructed of laminated veneer lumber, a sustainable building product grown and manufactured locally (source: Carl Devereux)

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**Canterbury Earthquakes   
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Section 1:

Introduction

The Canterbury earthquakes have significantly tested the performance of old and modern buildings in the Christchurch Central Business District (CBD). They have led to debate as to the adequacy of current building and construction technologies and the performance objectives of the current design standards.

## 1.1 Impacts of the Canterbury earthquakes

One major repercussion of the Canterbury earthquake sequence has been the significant damage to buildings. Investigations have resulted in around 200 buildings with five or more storeys being assessed as dangerous and requiring stabilising, and half of these are already marked as non-repairable. In March 2012 the Canterbury Earthquake Recovery Authority (CERA) advised the Royal Commission that it estimated the total value of buildings requiring demolition or being demolished was around $1.5 billion. In addition, the Treasury’s Pre-election Fiscal and Economic Update released in October 2011 noted that damage estimates from the Canterbury earthquakes were around $20 billion, of which $4 billion was attributed to the commercial sector. Treasury stated that the cost might be as much as $30 billion if additional costs such as business disruption, inflation, insurance administration and rebuilding to higher standards than before the earthquake were taken into account.

The damage to buildings can be categorised in various forms, in order of increasing severity:

1. Building damage caused by shaking:

a) Damage to non-structural components (repairable)

b) Minor repairable structural damage

c) Major structural damage requiring demolition

d) Collapse.

2. Damage caused by liquefaction and lateral spreading:

a) Uneven settlement (repairable)

b) Severe tilting (non-repairable).

The 22 February 2011 earthquake was an extreme and rare event, with many CBD buildings experiencing inertial forces much greater than those considered in their design. The Pyne Gould Corporation (PGC) building (designed in 1963) and Canterbury Television (CTV) building (designed in 1986) both collapsed catastrophically. Apart from those two buildings (and the exceptions of the performance of stairs, attachment of panels and some non-structural elements), other modern buildings met the goal of life-safety that underpins New Zealand’s current building regulatory regime. In most cases, however, this was accompanied by major structural and non-structural damage.

The extent of structural damage in many buildings eventually resulted in their demolition rather than repair, with CERA estimating that 1100 buildings in the CBD will be fully or partially demolished. The number of demolitions, the cost of repairs to structural and non-structural damage, and the business disruption in the Christchurch CBD for 17 months to date has had substantial economic and social impacts.

A majority of the older unreinforced masonry (URM) buildings and stone churches have suffered severe damage or partial collapse. These buildings have long been known to be vulnerable in an earthquake. They are discussed in Volume 4.

## 1.2 Lessons to be learned

The Royal Commission’s Terms of Reference describe two different inquiries: one relating to the performance of buildings in the Canterbury earthquakes and the other being more forward looking. The second part of the Inquiry requires us to consider the adequacy of the current legal and best practice requirements for the design, construction and maintenance of buildings in central business districts throughout New Zealand. We are also required to make recommendations on:

• any measures necessary or desirable to prevent or minimise the failure (that is, damage, collapse or other failure) of buildings in New Zealand due to earthquakes likely to occur during the lifetime of those buildings;

• the cost of those measures; and

• the adequacy of legal and best practice requirements for building design, construction and maintenance insofar as those requirements apply to managing risk of building failure caused by earthquakes.

The Royal Commission’s Report discusses buildings that performed poorly during the Canterbury earthquakes as well as some that performed well. Leaving aside those buildings that have been identified as affected by various structural weaknesses, many have been damaged beyond economic repair simply because, although they complied with the relevant construction and materials standards, they were subjected to a level of shaking much greater than the specified design level. Current design practice requires structures to be ductile, as this enables buildings to survive a major earthquake without collapsing. Current practice is to provide this ductility by yielding of reinforcing steel or structural steel members, which causes structural damage.

Post-earthquake, it is apparent that building owners and others affected had different expectations of the likely behaviour of an “earthquake-resistant” building. While all expected life-safety and collapse prevention, the observed level of damage was clearly not anticipated by many building owners and occupiers. A large part of the explanation for the damage that occurred is, of course, the magnitude of the earthquakes, and in particular the severity of the February 2011 event. But the severe economic and socio-economic losses caused by the earthquakes are a matter for national as well as local concern. The cost of damage includes loss of use as well as repair or replacement of the physical asset. While the Royal Commission acknowledges the need (which will be ongoing) for careful consideration of risk and cost, we consider that it will be desirable to lessen the potential for economic loss as a result of future earthquakes.

## 1.3 Achieving a better performance

Seismic design philosophy and performance-based criteria outline the expectations of building performance in terms of the predicted average return periods of given-magnitude earthquakes. There are a number of options that can be adopted to achieve better building performance. One is to increase the level of seismic design actions (that is, design for earthquakes of increased magnitude). A second, discussed in section 9 of Volume 2, is to make incremental improvements in the technical aspects of current design practice, without increasing the level of seismic design actions other than in accordance with the normal process by which knowledge about seismicity becomes incorporated in the Earthquake Actions Standard. A third option is to employ a different approach, focusing on low-damage design. This is the option discussed in this Volume.

## 1.4 Low-damage technologies

Alternative methods are emerging as a way of reducing damage sustained in earthquakes. The general objective of these low-damage technologies is to design new forms of lateral load resisting structures, where damage is either suppressed or limited to readily replaceable elements. Successful implementation of this approach could remove or reduce the damage sustained in a major earthquake and the expensive downtime that follows.

Low-damage solutions are not properly viewed as a new concept: base isolation, for example, has been in use for over 30 years. Although some low- damage building measures can be incorporated into conventional structural systems, most research is concentrated on developing new structural systems or devices that will deliver improved building performance.

## 1.5 Hearings and expert reports

Over 12–14 March 2012 the Commission conducted a public hearing focusing on the wide range of new building technologies that might be relevant to the rebuild of Christchurch’s CBD and potentially to new buildings in other New Zealand CBDs.

This hearing had three principal objectives. The first was to hear evidence and discussion about low- damage building technologies, some of which are already being implemented in New Zealand while others are still developing. The second was to consider a range of views on the building performance objectives used as a basis for design, along with the associated economic impacts. The third was to consider the regulatory environment within which innovation occurs.

Presenters included academics, practising engineers, architects and representatives of professional engineering organisations. A list of these experts is in Appendix 3 of Volume 1 of this Report.

The Royal Commission obtained two technical reports relevant for this hearing, which were:

• Structural Design for Earthquake Resistance: Past, Present and Future (“the Dhakal report”)1; and

• Base Isolation and Damage-Resistant Technologies for Improved Seismic Performance of Buildings (“the Buchanan report”)2.

Section 2:

Seismic design philosophy

## 2.1 History and development

Past earthquakes around the world that have inflicted damage and casualties have been followed by advances in seismic design. This sequence of learning from disasters and improving the design practice is a constant cycle.

Modern design philosophy accepts structures that respond to seismic ground motions in an inelastic manner without collapse. Structures designed in this way will sustain damage in earthquakes that are less intense than the specified ultimate limit state (ULS) level of shaking predicted at a site for a given return period. Design has developed through several phases known variously as load and resistance factor design, limit state design, capacity design and performance-based design. These phases are discussed in more depth in the Dhakal report.1

The current seismic design methods are characterised by an aim to ensure life-safety by preventing collapse in major earthquakes and to limit structural damage in more frequent, moderate earthquakes.

Some research into building performance has focused on the economic implications of a seismic event and the possibility of differing levels of building performance in accordance with a building owner’s requirements. Notions of damage and downtime reduction are not necessarily new, but the recent devastation caused by the Canterbury earthquakes has renewed interest in damage reduction.

The adoption of low-damage technologies is one way that improved performance levels might be achieved. Before discussing them, it will be appropriate to address the current approach to earthquake design and the possible basis of a new approach.

## 2.2 Seismic performance criteria

### 2.2.1 Present framework

The New Zealand Building Code is performance-based and sets out the minimum performance requirements for buildings. Unlike a prescriptive code, it does not specify how to achieve this performance (that is, there are no detailed requirements for design and construction). Performance-based regulation focuses on the outcomes envisaged for a building and less on specific materials, assemblies, construction and installations. In practice, this means there can be many ways of meeting the requirements. The Building Code allows flexibility and enables designers and the industry to develop innovative and cost-effective solutions.

The Building Code system also provides for the publication of prescriptive information (compliance documents) about designs that provide specific ways of meeting the relevant Building Code requirements. Buildings built using the method described in a compliance document will be accepted as complying with the Building Code. Compliance documents may be verification methods, which are tests and calculations by which a design may be evaluated for compliance with the Building Code. Or they might be acceptable solutions, which are a prescriptive means of complying with the Building Code.

Other methods can be used, provided they demonstrate that the performance requirements of the Building Code have been met. They are often referred to as “alternative solutions”. This is currently the primary pathway for a majority of the low-damage building technologies.

Currently, seismic design codes require structures to satisfy more than one seismic performance requirement. The present performance-based design objectives specified in New Zealand codes are based on an international best practice philosophy. The Structural Engineers Association of California (SEAOC) Vision 2000 Committee (1995) produced a matrix similar to that shown in Figure 1 (page 6). SEAOC comprehensively defined performance-based seismic engineering as consisting of:

|  |
| --- |
| …a set of engineering procedures for design and construction of structures to achieve predictable levels of performance in response to specified levels of earthquake, within definable levels of reliability.3 |

The general objectives of seismic design philosophies or codes (as shown in Figure 1) was described at the hearing by Professor Andrew Buchanan as a combination of the following three broad performance objectives:

1. A minor, frequent earthquake should cause no damage.

2. A moderate earthquake may cause repairable damage.

3. A severe earthquake may cause extensive damage but no collapse or loss of life should occur.

The New Zealand Standards, AS/NZS 1170.04 and NZS 1170.55, use two design levels: Serviceability Limit State (SLS) and Ultimate Limit State (ULS).

Both limit states are explained in section 3 of Volume 1 of this Report. The SLS generally covers the first objective and the ULS largely covers the others.

The New Zealand Building Code and Standards do not explicitly require a building to be checked for collapse prevention in the Maximum Considered Earthquake (MCE). However, the conservative aspects of designing for ULS (that is, using the lower characteristic material strengths, strength reduction factors, etc.) gives a structure protection against collapse in an earthquake above the ULS design level of shaking.

These performance objectives are qualitative in nature. Figure 1 illustrates a modified SEAOC performance-objective matrix, where the stated return periods indicate how frequent, occasional and rare earthquakes may be defined.

A very rare, large magnitude earthquake (say a two per cent chance of occurring over the building’s design life) will likely result in significant damage to an ordinary building. The intended level of performance also depends on the importance of a structure. The angled lines in Figure 1 represent different categories of building importance. It can be seen that for an earthquake with a 2500-year return period, the goal for safety critical facilities (for example, a hospital) is to try to achieve an operational performance level.

With a performance-based approach, the design is based on the specified performance for damage avoidance and life-safety. Within this proposed framework, expected or desired performance levels are correlated with levels of seismic hazard risk.

Figure 1: Performance-objective matrix (modified from Vision 2000 Performance Objectives)



### 2.2.2 Future developments for performance objectives

In the last decade a considerable international effort has been dedicated to the development of new design methods and new technology to ensure better damage control in major earthquakes.

In the Buchanan report the view expressed was that the required performance criteria should be changed, with the objective of all building types being repairable after a major earthquake regardless of the Importance Level. This is shown in the modified performance- objective matrix (Figure 2) by a shift of the objective lines to the left. Note that the fully operational and operational performance levels are considered to be economically repairable, whereas the life-safe and near collapse performance levels are unacceptable because demolition would be required.

Research into a concept called Loss Optimisation Seismic Design (LOSD) has been ongoing at the University of Canterbury.1 LOSD has two performance objectives, the first being life-safety and the second being the minimisation of earthquake-induced loss. LOSD focuses on the performance of structural and non-structural elements and contents along with the associated downtime, as these all contribute to the total financial loss incurred in a building during an earthquake. Investigation is under way to develop performance-based frameworks that enable the building performance to be measured in terms of predicted repair costs, casualties and the number of days of downtime. However, the practical application of this is still some years away.

Professor Rajesh Dhakal explained that by presenting these performance measures in an easily understood format for building owners, tenants and insurers, the information could then be compared with other hazards that affected the building. He said that evaluating and interpreting the risks in terms of such generic parameters should lead to more effective decision making through better understanding and improved allocation of resources.

Figure 2: Proposed modification to performance-objective matrix (source: Buchanan report)

