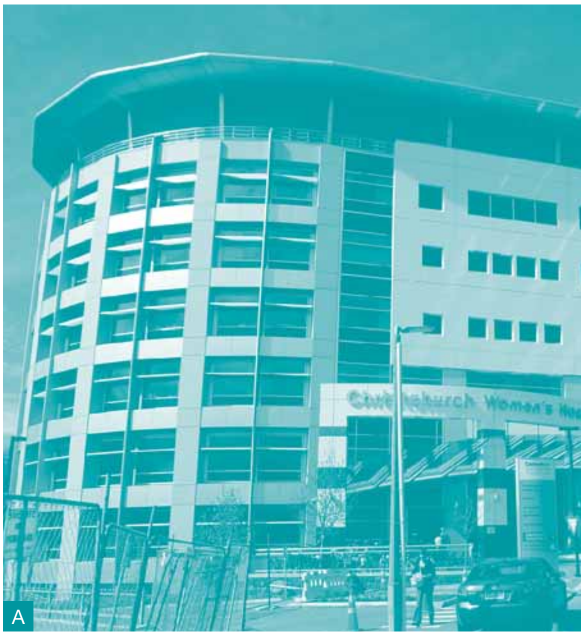
Canterbury Earthquakes
Royal Commission
Te Komihana Rūwhenua o Waitaha

H.2

FINAL REPORT

VOLUME 3
LOW-DAMAGE BUILDING TECHNOLOGIES



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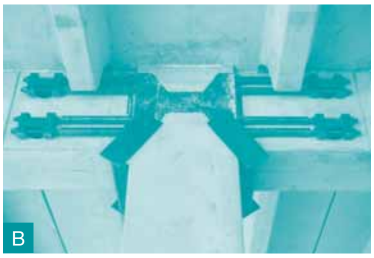

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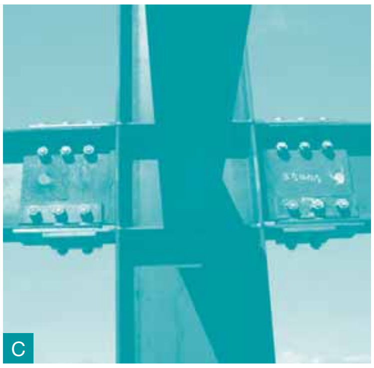

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A. The Christchurch Women's Hospital was the first base-isolated building in the South Island, opened in 2005. The lead rubber bearings located at the underside of the lower ground floor add flexibility to the building, giving a more gentle rolling 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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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 1170.0[4] and NZS 1170.5[5], 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.

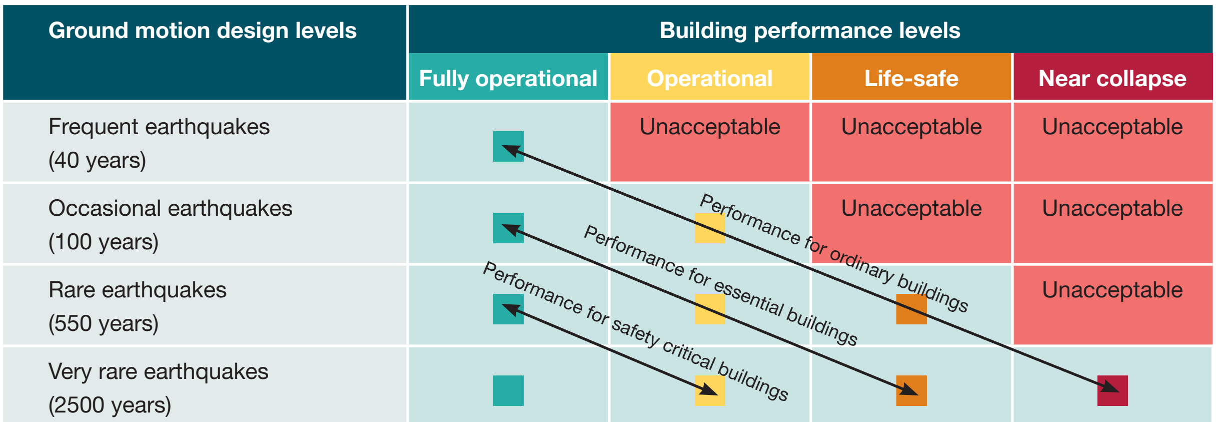


Figure 1: Performance-objective matrix (modified from Vision 2000 Performance Objectives)

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.

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

Basic objective

Essential objective

Safety critical objective

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

Section 3: Low-damage building technologies

3.1 Introduction

Low-damage technologies are being developed that aim to achieve a better building performance by reducing damage in major earthquakes. At the hearing Professor Desmond Bull expressed the view that the engineering profession might have thought that the damage sustained in conventional capacity-designed buildings was repairable, but for various reasons this had not been the case following the February earthquake, with full demolition often considered preferable.

Professor Stefano Pampanin described the low-damage technologies as giving greater building resilience by providing damage reduction in the primary structural systems, with the potential to reduce damage to non-structural elements and building contents by damping, isolation or careful detailing. The minor damage inflicted by a design level event may be easily and economically repaired, with minimal disruption and minimal downtime for building users. For new buildings, the low-damage technologies have been developed specifically to be incorporated into the structure at a comparable cost to conventional systems using common construction practices. The low-damage concepts can also be applied to existing buildings by retrofit techniques, although this is a more difficult task.

The low-damage technologies are all inter-related and are not mutually exclusive. However, they can conveniently be described in two main categories:

1. **Methods of controlling seismic response**. Base isolation combined with supplemental damping, which is an energy-dissipation device, to control the response of a building by reducing accelerations and the building's displacements.
2. **Emerging forms of low-damage technology**. These come in various types. Many incorporate rocking mechanisms in conjunction with energy-dissipation devices, which act as ductile regions, absorbing energy without any significant structural damage. Most of these structural systems can be constructed from concrete, steel or timber.

Low-damage building technologies are sometimes referred to as "damage-resistant" technologies. This terminology should be used with care, as it is not possible to design and build structures that are damage-resistant under all earthquakes, as the term may suggest. In the context of the Buchanan report, "damage-resistant" means that there should be less damage than in existing construction as a result of a design level earthquake.

These low-damage technologies are at various stages of development. There has been a significant research effort into the development of low-damage design systems, such as Precast Seismic Structural Systems (PRESSS), steel friction dampers and rocking timber systems (Pres-Lam), with some buildings already completed. Mr John Hare, President of the Structural Engineering Society New Zealand Inc. (SESOC), expressed the view at the hearing that it is important that these systems genuinely deliver on their prescribed performance objectives and do not introduce unknown future problems. A set of properties to determine the effectiveness of low-damage technologies has been proposed by Mr Hare.[6] The properties of a low-damage system can be characterised and assessed under the following six categories:

1. Damage mitigation effectiveness.
2. Repairability.
3. Ability to self-centre.
4. Non-structural and contents damage.
5. Durability.
6. Affordability.

We consider that there is merit in this approach. We note also that conventional structural systems usually provide for secondary load paths, so that if one critical component fails, there is an in-built fail-safe mechanism. Low-damage technologies should also seek to satisfy this criterion.

The seismic analysis methods are an important component of the design. Professor Nigel Priestley gave evidence on the displacement-based design (DBD) of structures. He described the advantages of this emerging approach and methods for its application.[7]

Dr. Didier Pettinga described the practising engineer's perspective and benefits of being able to use both DBD and force-based design (FBD) in different situations. A major advantage with FBD is the amount of software that has been written for its use. The Royal Commission can see the value in being able to use both approaches. The DBD has some potential advantages in the analysis of buildings where low-damage technologies are used. Both approaches have a range of assumptions and simplifications; therefore, a designer should carefully select a method or combination of methods to best model the real-life building behaviour.

3.2 Methods of controlling seismic response

3.2.1 Base isolation

3.2.1.1 The concept

The goal of base isolation involves separating the building from the ground so that violent earthquake motions are not transmitted directly into the structure. In simple terms, it is equivalent to adding a horizontal suspension system to the building. This adds flexibility at the level of the isolators, giving a stiff building a more gentle rolling motion during an earthquake. Base isolation is not a solution for all building types and in some cases can actually worsen effects. Expertise and careful consideration are required when using this technology.

The mechanism of base isolation is described schematically in Figure 3. In conventional construction, a building is rigidly connected or fixed to its foundations as shown in Figure 3(a). A perfectly isolated building, say, on frictionless rollers as in Figure 3(b), would remain stationary while the ground moved beneath it. A few fundamental problems with this, if it was achievable, are that the building would start to move under other external forces such as wind, and after an earthquake the building could end up some distance from where it started. In practice, devices are installed at an isolated plane, usually at the level of the foundations, to allow for controlled movement as in Figure 3(c).

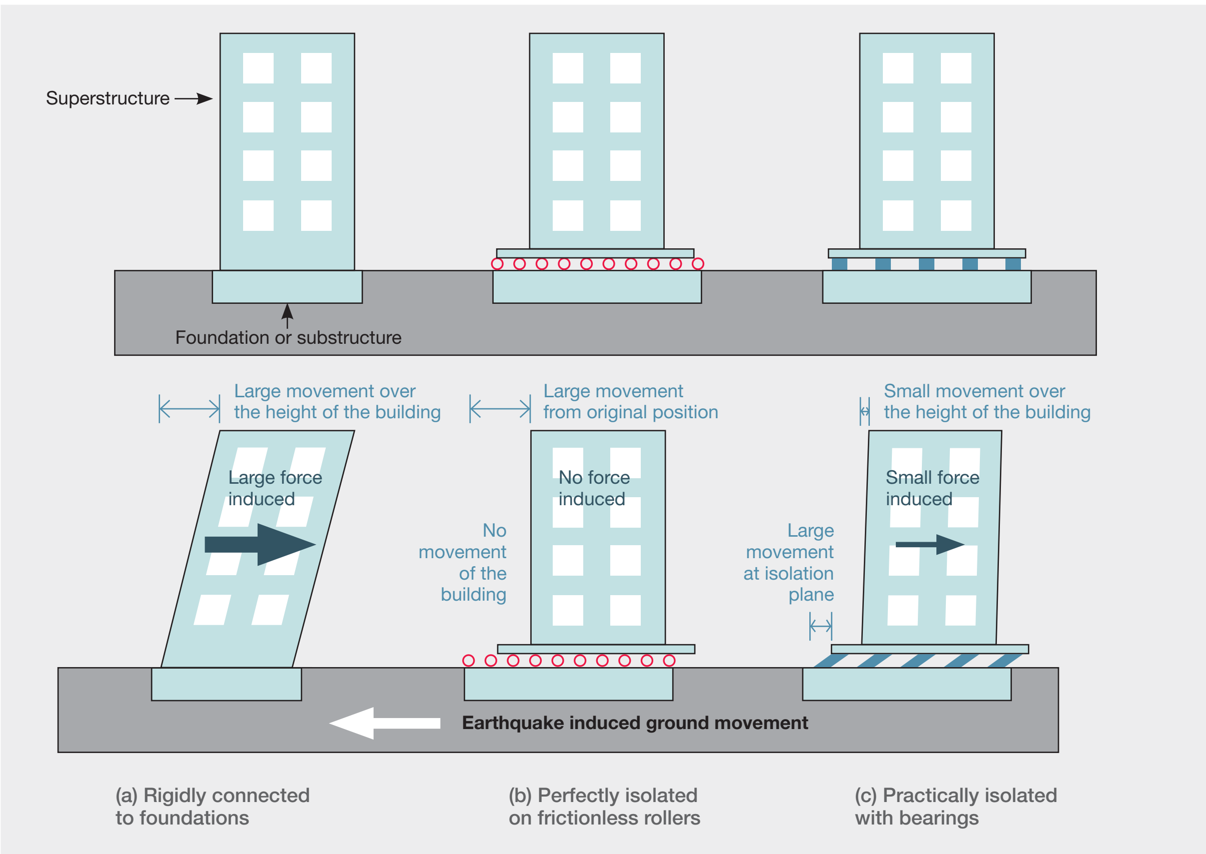


Figure 3: The concept of base isolation

The modern form of base isolation is considered a mature technology and has been used in buildings since the late 1970s. The Royal Commission heard evidence from Mr Trevor Kelly, a technical director at Holmes Consulting Group, who is well familiar with this technique. He said that impediments to the adoption of base isolation are lack of awareness and understanding, misconceptions about its cost, an unsupportive regulatory framework and the perception that little is known about its performance in a real earthquake.

In fact, the performance of base-isolated structures has been tested and documented in a number of significant earthquakes in North America, Japan and New Zealand. An example is from the 1994 Northridge earthquake, where the base-isolated University of Southern California Hospital remained undamaged while other modern buildings in the same area had non-repairable damage.

Mr Kelly stated that after the 2011 Japan earthquake, a survey was carried out on the performance of buildings that incorporated some form of vibration control. The survey reported that around a third of those buildings suffered some form of damage "resulting from the dampers or moving parts not functioning properly". The failure of some isolation devices is of interest, as these real-life events show up weaknesses (such as durability issues) not seen in laboratory tests, and possibly can be used to help refine current procedures.

3.2.1.2 Technical aspects

The primary benefit of base isolation is the decrease in base shear forces and floor accelerations. The extent of the benefit will depend on the dynamic characteristics of the building, the soil type, the magnitude of the earthquake and its proximity to the fault.

The most fundamental aspect is called the period shift. The flexibility of the isolators increases the period of response of the structure in a major earthquake, and this generally reduces the acceleration (as shown in Figure 4(a)). This is accompanied by an increase in displacement as seen in Figure 4(b). However, this displacement occurs primarily in the base isolation devices instead of in the building structure itself. This aspect can be thought of as the spring and gives a more gentle rolling motion.

The second key characteristic is damping. The damping is typically taken as five per cent for a non-isolated structure. With the higher (typically 25 per cent) damping in a base-isolated structure, there are two effects. First, it reduces the acceleration further, as shown in Figure 4(a); and second, it reduces the displacement, see Figure 4(b). This characteristic can be compared with the effect of shock absorbers in a motor vehicle. They reduce how much you bounce and also bring you back to rest much more quickly.

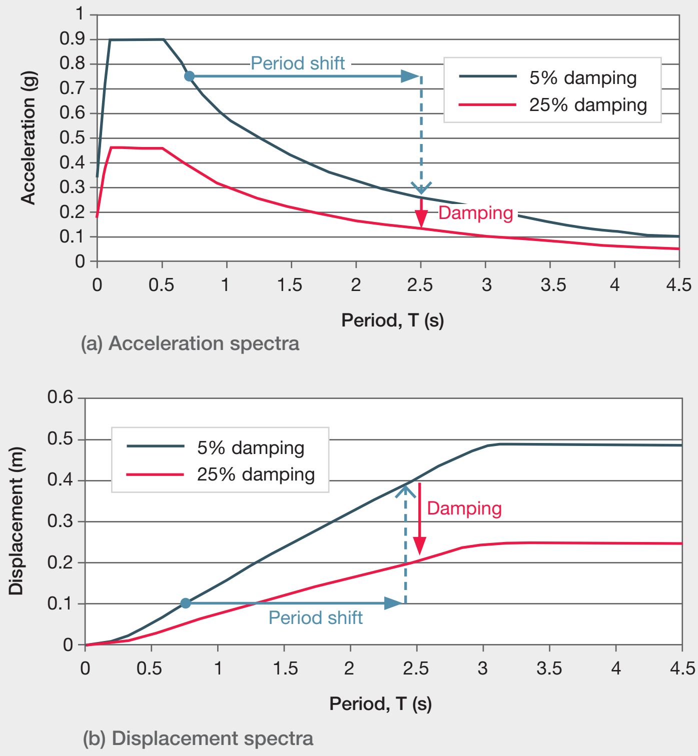


Figure 4: Technical aspects of period shift and damping

Base isolation is not suitable for all soil types as soft soils transmit more earthquake energy in the long period range, which means isolation is less effective. The design spectra in NZS 1170.5 are classified into five different soil types. Stiff soil and rock sites have acceleration coefficients that decrease more rapidly in the longer-period ranges compared to design spectra for soft-soil sites. Therefore, the reduction in acceleration caused by period shift would be less for a soft-soil site than a stiff-soil site.

Another effect is the near-fault effect, where the epicentre of the earthquake is close to a building. A near-fault effect increases displacements and accelerations in the long-period range. It has a similar effect to the soft-soil effect, with increases in both acceleration and displacement. In NZS 1170.5 a near-fault effect applies to structures within 20km of a major fault and for any period greater than 1.5 seconds. Hence, most base-isolated structures in high-seismicity areas will be affected as they typically have a period greater than 1.5 seconds.

Another consequence of base isolation is rigidity under small and frequent service lateral loads such as wind and traffic vibrations. When designing a building to resist very large earthquakes, the stiffness of the isolator may be set quite high. It is therefore important to remember that in smaller earthquakes, the building will act similarly to a structure that is not isolated.

3.2.1.3 Types of base isolators

The bearings used to isolate buildings come in a range of different forms and are the subject of a number of patents. The defining characteristic is that the system decouples the building from the ground motion by interposing a low horizontal stiffness. New Zealander Dr. Bill Robinson developed the lead rubber bearing, one of the most common base isolators used in New Zealand.

The lead rubber bearing consists of alternating laminations of rubber layers and steel plates. These are bonded together to provide vertical rigidity and horizontal flexibility, with a lead plug to provide stiffness (against wind loads for example) and energy dissipation in major earthquakes. The vertical rigidity means that the building is not isolated from seismic vertical accelerations and the lead plug has the disadvantage of allowing high-frequency accelerations to pass through it.

Other types of isolators include the laminated friction rubber bearing, steel yielding isolator, spherical rubber bearing and friction pendulum bearing or sleeved pile. Mr Kelly recommended that in determining the appropriate bearing system to use, the manufacturer and designer should collaborate to meet the unique performance requirements of the building. We agree with that approach.

Ms Megan Devine, General Manager of Robinson Seismic Ltd, stated that seismic isolation devices required no maintenance during the life of the building. However, after an earthquake they should be inspected to ensure that bolts and load plates were still in place.

She went on to indicate that generally there would not be a need to replace seismic isolation devices unless the event was significantly in excess of their design specification. In this case, some isolators should be taken out for testing to check their performance. We agree with Ms Devine's observations.

3.2.1.4 Suitability of base isolation

The technical aspects and considerations of period shift, damping, soil type and near fault can lead to parameters that determine whether a project is suitable for base isolation. Mr Kelly outlined these parameters as:

a) **Building:**
   The first consideration is the building itself. Since the fundamental benefit of isolating a building is the period shift, buildings best suited for isolation will typically have a period of less than one second, as the effectiveness of base isolation declines in taller, longer-period structures. Rocking of tall, slender buildings can also lead to tension forces in bearings, which make them poor candidates for base isolation even if they are not already ruled out by period.

b) **Site:**
   Firmer soils are more suitable for base isolation. As discussed earlier, softer soils make the base isolation less effective.

   In Mexico City, seismic waves bounce across a large alluvial basin at a period of about 2–2.5 seconds, thus creating resonance in a building in that period range. Designers should be aware of the possibility of this effect and consideration will be important for developments in Christchurch. Response spectra from the 4 September 2010 and 22 February 2011 earthquakes show high displacements are induced in the period range of two to four seconds.[8] There may be a number of reasons for the amplified response in this period range, including the response of 300–500 metre thickness of alluvial soils that are overlain by 20–30 metres of recent soft soils. These two layers may interact to amplify excitation in the two to four second range. In addition, there may be some amplification associated with basin effects.[8]

c) **Space and installation:**
With base isolation, the reduced force comes with increased displacements. Buildings therefore require clearance around their perimeter. This is typically in the order of 250–1000mm and may rule out closely spaced buildings owing to loss of potential floor area.

This clearance must be maintained for the full life of the building and may require periodic inspection to ensure it is not compromised. Any services, utilities and any other components between the ground and the building have to be specially detailed to allow for the design movement. Installation is also a challenge for existing buildings, as the building has to be supported while it is cut from its foundations and the bearings installed. Generally, only very important historic buildings will warrant this level of effort for a retrofit.

The natural candidates for base isolation have usually been:

- essential facilities such as hospitals that require continued functionality;
- historic structures and museums that have low available ductility, valuable contents and require preservation; and
- manufacturing facilities that have high-value contents and require continued functionality.

The stiffness and strength requirements are similar for base-isolated and normal ductile designed buildings, with the ductile detailing perhaps less onerous for base-isolated buildings.

Mr Kelly described a misconception that the reduction of inertial forces owing to base isolation will result in smaller structural members than in conventional buildings. This is not the case, owing to ductility. Base isolation reduces the forces typically by a factor of three to four. However, conventional buildings are also designed for similarly reduced forces in designing for ductility.

The key benefit is that base isolation reduces the amplitude of the horizontal ground motions transmitted into the structure. This makes it the leading technique to protect contents and non-structural elements, which are generally a high proportion of the total cost of a building. Accompanying this reduction in damage is the prospect of continued functionality immediately after the earthquake event.

3.2.2 Supplemental damping devices

Mr Hare observed that one of the dilemmas a designer faces at the conceptual stage is whether to design a stiff building with smaller lateral displacement and high accelerations, or a more flexible building with higher displacement to reduce floor accelerations. Reducing lateral displacements will result in less damage to non-structural components (that is, cladding) but the floor accelerations will be higher and the motion more violent for occupants and building contents. A flexible building will have the opposite effect. One way to improve both aspects is supplemental damping, which can reduce both acceleration and displacement.

Supplemental damping provides a mechanism for the dissipation of seismic energy in a controlled manner. Damping devices can be used in a range of applications and can be incorporated into new buildings or retrofitted. They can be placed at foundation level or elsewhere in the structure at diagonal braces and at the rocking joints. Supplemental damping is generally used as part of base-isolation schemes, or alone in tall buildings that cannot effectively be base-isolated.

Professor Pampanin explained that cost-efficient, externally located supplemental dampers are being developed. These can, if required, be easily removed and replaced after an earthquake event. This type of structure allows for a modular system with replaceable sacrificial components that act as energy-dissipation devices at the rocking connection. Together, the rocking joint and the energy-dissipation device have a similar action to a plastic hinge. However, while a plastic hinge is very difficult to replace and repair after a major earthquake, it is a relatively simple matter to replace or repair an energy-dissipation device.

There are three broad categories of damper: viscous dampers, friction dampers and yielding dampers. These employ various mechanisms to convert earthquake energy into heat.

3.2.2.1 Viscous dampers

As explained in the Buchanan report, viscous dampers (also called fluid viscous dampers) function by the movement of the fluid or by the plastic extrusion of lead within a cylinder, as shown in Figure 5(a) and (b). The high-force-to-volume (HF2V) or lead-extrusion dissipater works by having a bulged shaft that passes through encased lead.

These devices can be used in diagonal braces or a rocking interface. Figure 5(c) shows dampers connected to a foundation and a rocking timber element.

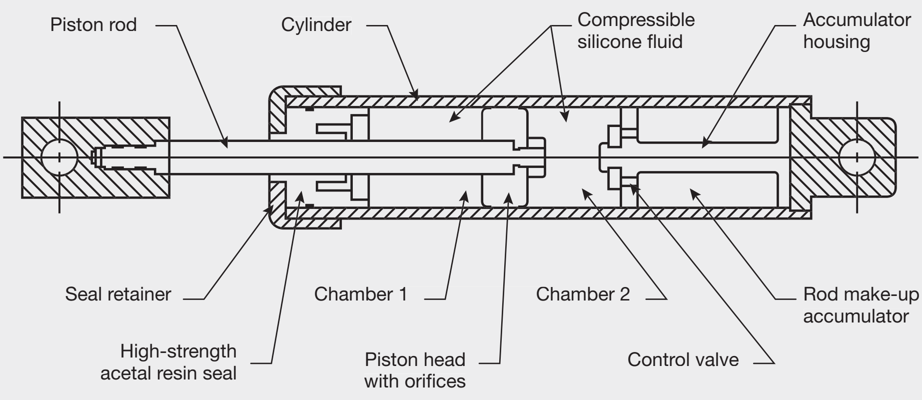
A limitation is that some of these devices are expensive.

3.2.2.2 Friction dampers

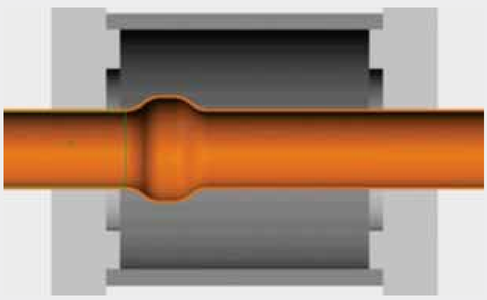
Friction dampers are used with low-damage steel and timber structures, and can be used in moment resisting frames, diagonal braces or rocking walls. Usually two metal surfaces are clamped together with bolts in slotted holes. The main concern with this device is durability. Currently, it is only recommended for use in dry internal environments. Accelerated corrosion testing is under way at The University of Auckland.

3.2.2.3 Yielding dampers

Yielding dampers (also called hysteretic dampers) are typically made of ductile steel, which yields and deforms plastically. The buckling restraint brace (BRB) comprises a yielding steel core that is encased to prevent buckling when the brace goes into compression. The steel core is debonded from the surrounding material so that it can freely slide, as shown in Figure 6(a). This ensures the brace has a similar strength and stiffness in both tension and compression. Professor Charles Clifton said in evidence that the BRB can be used in new construction or as a retrofit to various structural systems. Proprietary BRBs are common in Japan and North America. In Professor Clifton's view, the small New Zealand market and its distance from the main suppliers mean that these proprietary products are unsuitable for here. He believes a better option is to develop an equivalent BRB for use in New Zealand. A research project at The University of Auckland is finalising a design procedure for a BRB, as shown in Figure 6(b).



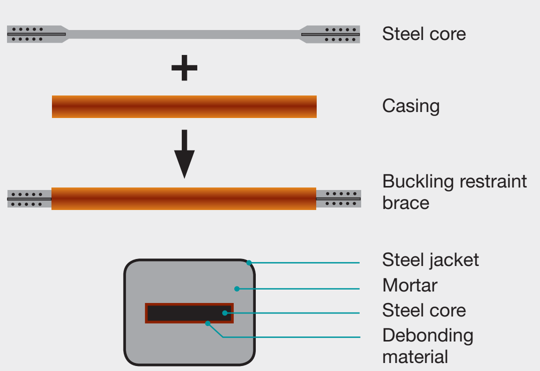
(a) Fluid viscous damper



(b) Lead extrusion damper

(c) Application to the base of a rocking timber element in the laboratory

Figure 5: Viscous dampers (source: Buchanan report)

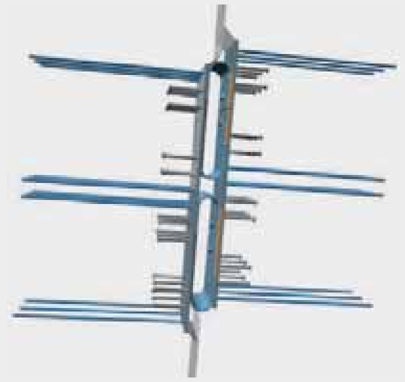


(a) Diagonal BRB components (source: Buchanan report)

(b) BRB being tested at The University of Auckland (source: Clifton presentation)

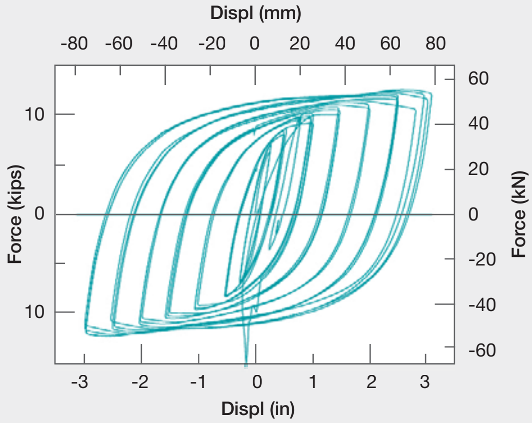
Figure 6: Buckling Restraint Brace (BRB)

Another form of hysteretic damping device, shown in Figure 7(a) and (b), can be placed between concrete or timber rocking walls. The U-shaped flexural plate (UFP) was developed by a New Zealand pioneer in this field, Dr. Ivan Skinner. It is a simple device that has been thoroughly tested in laboratories. The very good energy dissipation obtained with this device is shown in Figure 7(c).



(a) UFP detail for concrete walls

(b) Detail of one UFP for timber walls



(c) Hysteresis behaviour of U-shaped flexural plates

Figure 7: U-shaped flexural plate: typical details and characteristics (source: Buchanan report)

Further information about the different types of dampers and their application to different structural forms in concrete, steel and timber can be found in the Buchanan report.

3.2.3 Examples of base isolation and supplemental damping devices

The William Clayton building (Figure 8(a)), constructed in Wellington in the late 1970s, was the first base-isolated structure to use lead rubber bearings. Other buildings have followed, including the Museum of New Zealand Te Papa Tongarewa and Parliament Buildings (an example of a seismically retrofitted building) in Wellington, and various regional hospitals. The Christchurch Women's Hospital is the only base-isolated building in the South Island. Lead rubber bearing systems have been extensively used for base isolation in Japan, China, California and elsewhere.

An example of a building incorporating supplemental damping devices with a novel method of base isolation is the Union House building, built in the 1980s on the Auckland waterfront (see Figure 8(b)). This structure dissipates seismic energy through flexural yielding of steel members located near its base. The building is isolated on long piles in sleeves that allow lateral movement. Ms Devine stated in evidence that there had been a seven per cent saving on the total construction cost ($6.6 million) thanks to a three months' shorter construction time.

(a) William Clayton building, Wellington (source: Richard Sharpe)

(b) Union House building, Auckland (source: Trevor Kelly)

Figure 8: Buildings incorporating methods to control seismic response

3.2.3.1 Case studies

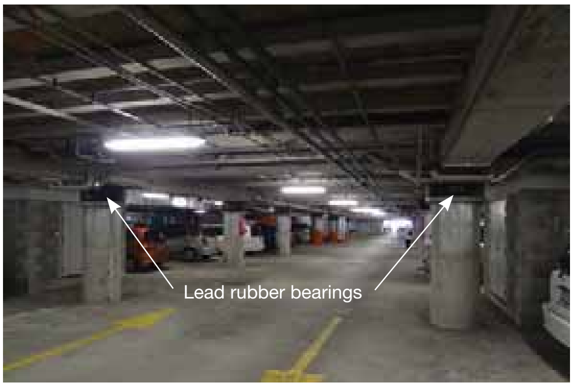
The Royal Commission heard evidence from Ms Devine and from Mr Grant Wilkinson, Managing Director of Ruamoko Solutions Ltd, about three recently built or forthcoming base-isolated buildings in New Zealand.

Cost figures for two hospitals were quoted by Ms Devine and are given below. They came from a study by Professor Andrew Charleson and Nabil Allaf from Victoria University of Wellington.[9] Professor Charleson gave evidence at the hearing.

Case 1: Wellington Regional Hospital

Completed in 2008, the seven-storey Wellington Regional Hospital (see Figure 9(a)) incorporates a two-storey podium, and has a total floor area of 44,700m^2. The total construction cost was $165m, including structural and non-structural components as well as the fit out of the building. It has 135 lead rubber bearings and 132 slider bearings, provided at a cost of about one per cent of the total construction cost. Other associated costs included providing flexibility to services at the isolation plane, the seismic gap (or "moat") and suspended floors. This gave a total base isolation system cost of around three per cent of the total construction cost, or $110 per square metre. The basement cost an additional five per cent of total construction costs on top of this three per cent, but this space is now used for parking (Figure 9(b)) and provides an ongoing source of income.

(a) Building elevation



(b) Parking area with base isolators

Figure 9: Wellington Regional Hospital (source: Andrew Charleson)

Case 2: Christchurch Women's Hospital

The Christchurch Women's Hospital was opened in 2005 and is shown in Figure 10(a). The evidence given to the Royal Commission was unclear as to its total construction cost: that was either $50 million or $60 million. The building has a total floor area of 20,000m^2 spread over nine levels. It was designed to withstand an earthquake with an expected return period of 2500 years. Mr Wilkinson stated that in selecting base isolation, the building owners were mindful of the added seismic security that the system brought. During the February earthquake, scratch marks were left on steel plates bridging the seismic gap. These marks indicated that lateral movements of ±120mm had occurred.

A structural inspection report showed that the building performed as intended, sustaining only minor structural damage. It continued to be operational after the February earthquake. Some damage was documented that was potentially a consequence of the vertical accelerations, which were not isolated by the lead rubber bearings.

At about $10,000–$20,000 per isolator the cost amounted to a little under a million dollars, or about one to two per cent of the total construction cost. Additional costs involved architectural features (that is, stairs, elevators, seismic gap), utility and engineering design and a suspended floor above the isolators, all of which would not have been needed in a conventional building.

(a) Building elevation (source: Andrew Charleson)

(b) Lead rubber bearing (source: Buchanan report)

Figure 10: Christchurch Women's Hospital

Case 3: St Elmo Courts rebuild project

Mr Wilkinson gave evidence about the St Elmo Courts rebuild project, on Hereford Street in Christchurch. At the time of the hearing, in March 2012, this was at the detailed design stage and was expected to be the first base-isolated office building in the South Island. It is an example of a rebuild occurring on the Christchurch soils. Despite the site having good subsurface conditions, high scaling factors have been used in design for predicting the ground motions at the site. The cost of base isolation for this building was assessed in the design stage to be in the order of five per cent of the total construction cost.

The indicative costs stated above are only the direct costs and did not take into account any savings that might arise from using base isolation. In addition, given that the study by Professor Charleson was on hospitals, which have relatively costly mechanical services, the cost of base isolation as a percentage of the total building cost will be somewhat less than for other building types.

3.3 Emerging forms of low-damage technology

3.3.1 General principles

Research shows that low-damage design technology could limit structural damage in a major earthquake. Several methods use rocking connections, usually combined with supplemental damping devices, to absorb seismic energy. The combination of rocking connections and supplemental damping gives the structure a ductile characteristic, enabling it to be designed as a ductile structure with a reduced seismic response in a major earthquake. However, if these devices perform as intended, there is minimal residual damage to structural components. Regardless of the structural systems and devices used, the designer must carefully detail a building so that it behaves in an expected manner. As the late Dr. Thomas Paulay put it, the designer must “tell the structure what to do”.

3.3.1.1 Controlled rocking concept

Professor Pampanin explained that the idea of a rocking mechanism in structures has been around since ancient Greek times and more recently was employed in the 1970s on the South Rangitikei Railway Viaduct. The viaduct has slender piers that step, or rock, in a major earthquake. An analogy can be drawn to a person resisting a sideways pushing movement by rocking onto one leg and then returning to both, as opposed to standing firm to take the force. The principle is the same with modern structural rocking mechanisms, which use a high-strength, post-tensioned rod acting as a controller to ensure that the structure is clamped back into its original position after the shaking.

In the 1990s a major development in high-performance structural systems was the concept of ductile connections to accommodate high inelastic demand without suffering extensive material damage. A New Zealander, Professor Nigel Priestley, initiated the concept and then acted as the co-ordinator of the Precast Seismic Structural Systems (PRESSS) programme in the United States. The programme was prompted by the 1989 Loma Prieta and 1994 Northridge earthquakes, with testing carried out at the University of California at San Diego (see Figure 11). In PRESSS, prefabricated beams and columns (or walls) are joined together with steel tendons that have been post-tensioned to give rigid connections that rock under large lateral loads (as seen in Figure 12). The traditional plastic hinge mechanism is therefore replaced by a controlled rocking mechanism.

A "damage-control limit" state can be achieved under a design level earthquake (typically set at a 500-year return period), leading to an intrinsically high-performance seismic system in higher-intensity earthquakes. This technology has had significant testing with walls, where the post-tensioning goes all the way through to the foundations, as well as in frames, where the tendons pass through the beam-column joints.

(a) PRESSS frame

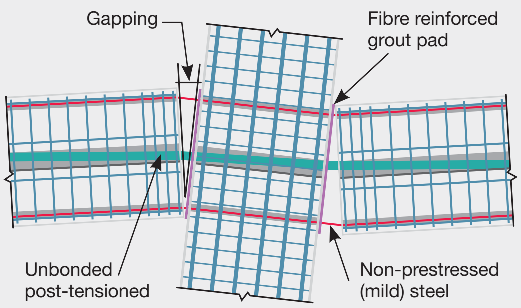
(b) PRESSS wall

Figure 11: Five-storey PRESSS Building tested at the University of California San Diego (source: Priestley et al, 1999[10])

Following theoretical development and large-scale testing, this approach has now been implemented in a number of buildings around the world. Guidance in New Zealand regulatory documents is very limited with only the Concrete Structures Standard NZS 3101, Appendix B[11] containing special provisions for the seismic design of these ductile-jointed precast concrete structural systems.

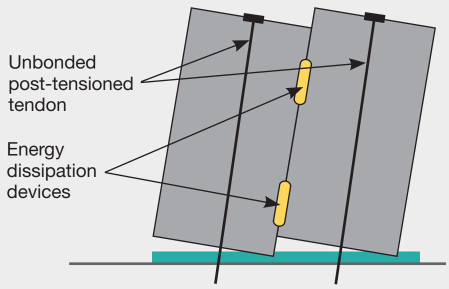
The PRESSS concept has been adapted for use in steel and timber structures. Its application in timber involves the use of highly engineered wood products. Post-tensioned timber structures, known as Pres-Lam, are recent technology that has arisen from research in New Zealand.

Frames



(a) Beam-column joint

Walls



(b) Coupled walls

Figure 12: Jointed rocking frame and wall systems illustrating the mechanism developed (source: Buchanan report)

The mechanism of gapping and the detailing for PRESSS frame and wall systems are shown in Figure 12. The system is sometimes called a “flag-shaped” hybrid system because of the way it self-centres and dissipates energy, as shown in Figure 13. The post-tensioning clamps the frame or wall to its original position, whereas partially debonded mild steel or other supplemental damping devices dissipate seismic energy through ductile yielding.

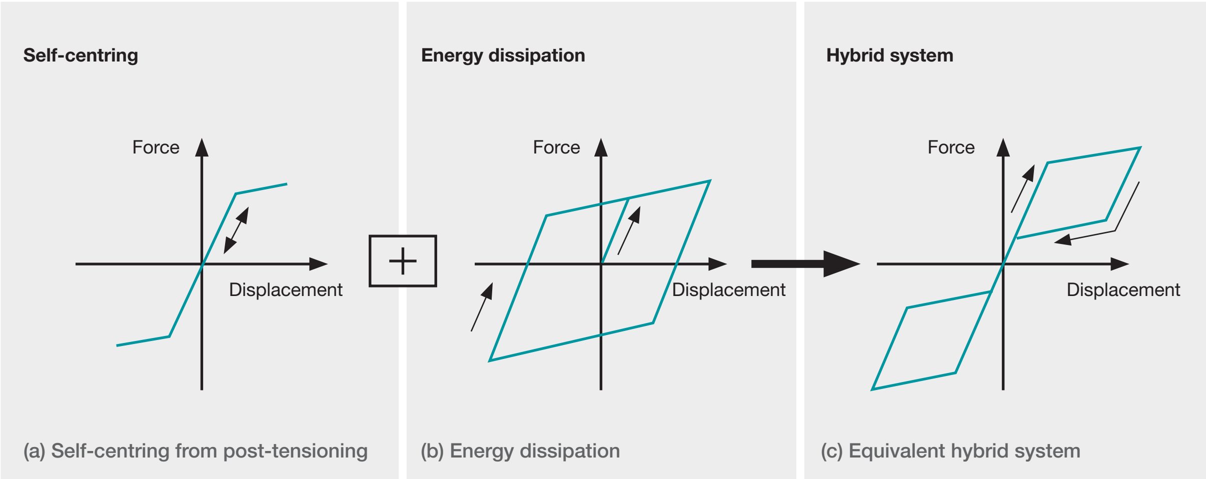


Figure 13: Hybrid system hysteresis for PRESSS (source: Buchanan report)

The PRESSS concept is less common in steel structures. Advances in low-damage design in steel structures use special detailing to allow for easily replaceable yielding elements or the incorporation of supplemental damping devices, such as friction sliding joints at connections.

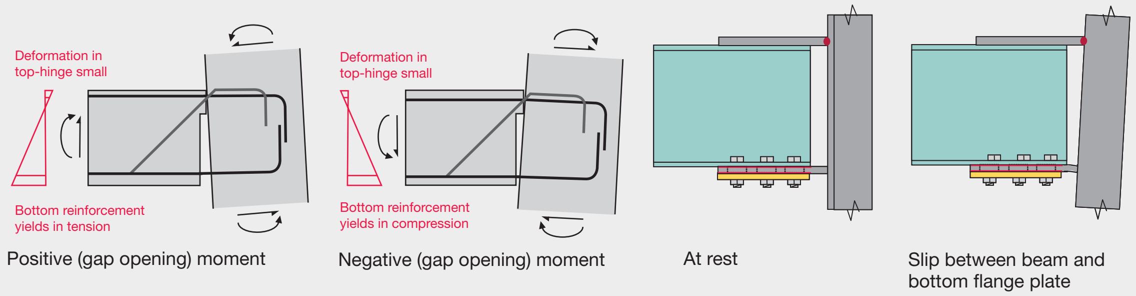
A problem with the PRESSS concept, which is discussed in the Buchanan report, is the displacement incompatibility that arises with floors in multi-storey buildings. This has the potential to cause significant damage to the floor slabs, which are mainly constructed from reinforced concrete. Professor Bull in his evidence emphasised that floors, acting as diaphragms, are critical structural elements tying the building together and distributing the seismic actions to the lateral load resisting elements. In jointed systems, the gapping that occurs between beams and columns has the potential to tear the floors and compromise load paths. The observation that this diaphragm damage is no worse than in a conventional reinforced concrete frame building is acknowledged, but it raises the question whether PRESSS adequately qualifies as a low-damage technology in all respects.

The Buchanan report does contain a number of proposed methods of overcoming the gapping problem in PRESSS buildings. However, we believe that the proposals may not be practical and further testing and development is required if the gapping problem is to be adequately addressed.

These low-damage technologies can be used in the retrofit of structures. Professor Pampanin addressed the idea of seismic weakening instead of strengthening. An example of this is a sawcut made at the bottom of an existing wall and combined with post-tensioning, so that a controlled rocking mechanism could be achieved.

3.3.1.2 The slotted beam and sliding hinge joint concept

The slotted beam or sliding hinge joint (SHJ) used in concrete, steel and timber construction can be used to minimise damage to concrete slab floors. The point about which rotation occurs is at the slab level, with the gap opening and closing at the bottom edge of the beam. Energy-dissipation devices are located at this bottom edge. Figure 14(a) shows the slotted beam concept in concrete structures; the steel beam with bolted friction plates is shown in Figure 14(b).



(a) Slotted beam for reinforced concrete (source: Desmond Bull)

(b) Sliding hinge joint (SHJ) for steel structures (source: Buchanan report)

Figure 14: Hinging or slotted beam mechanism

3.3.1.3 Benefits of low-damage technologies

Professor Pampanin described the structural advantages of PRESSS, Pres-Lam and the slotted beam or hinging technologies as follows:

1. Plastic hinge regions are replaced with jointed ductile connections, resulting in less structural damage to beams, columns and walls.
2. Post-tensioning, spring joints and other connected elastic elements enable the building to self-centre, resulting in little residual displacement after an earthquake.
3. The construction time is shorter as structural elements can be prefabricated off-site.
4. Quality assurance is better as structural elements are built in a controlled environment.
5. Construction uses conventional building components so it is not a vastly different technology for builders.
6. The reduced direct (structural repair) cost and indirect (business interruption) losses can result in significant savings after a major earthquake. Whether this last point might result in reduced insurance premiums or has implications for self-insurance is yet to be seen.

We accept this is a fair summary.

3.3.1.4 Important considerations

The Buchanan report outlined some important matters that must be considered when implementing low-damage design.

(a) Damage to floors

The majority of the building mass is in the self-weight of the floors and in the contents they are supporting. As the earthquake accelerates this mass, the forces induced must follow a load path into the lateral load resisting elements (that is, walls or frames) and ultimately into the ground. The floors also have the important function of tying the building together and transmitting lateral forces to the lateral force resisting elements. These forces act in the plane of the floor and are referred to as diaphragm forces.

Damage to the load paths in the floors can significantly compromise the building's performance and is an issue with both traditional and emerging technologies. Gapping and frame elongation that occurs with some rocking connections will inflict significant cracking of concrete and potential fracturing of reinforcing if it is not carefully detailed.

(b) Limiting slab damage

Some efforts have gone into solving the issue of slab damage. Each solution has its own limitations. The slotted or top-hinging beam concept minimises the gapping and frame elongation effects; other methods involve a system of isolating the slab in some way.

The articulated flooring systems and isolation of floor slabs are described in the Buchanan report and are summarised below.

The articulated flooring system is built so that it is partially detached from the supporting structure, with sliding joints or other innovation details, to avoid damage to the floor but to retain the essential diaphragm action (see Figure 15). In theory this system is able to accommodate the displacement incompatibility between floor and frame by creating an articulated or jointed mechanism that is decoupled in the two directions. However, we have difficulty in seeing how this proposal would work in practice in a building with more than one bay.

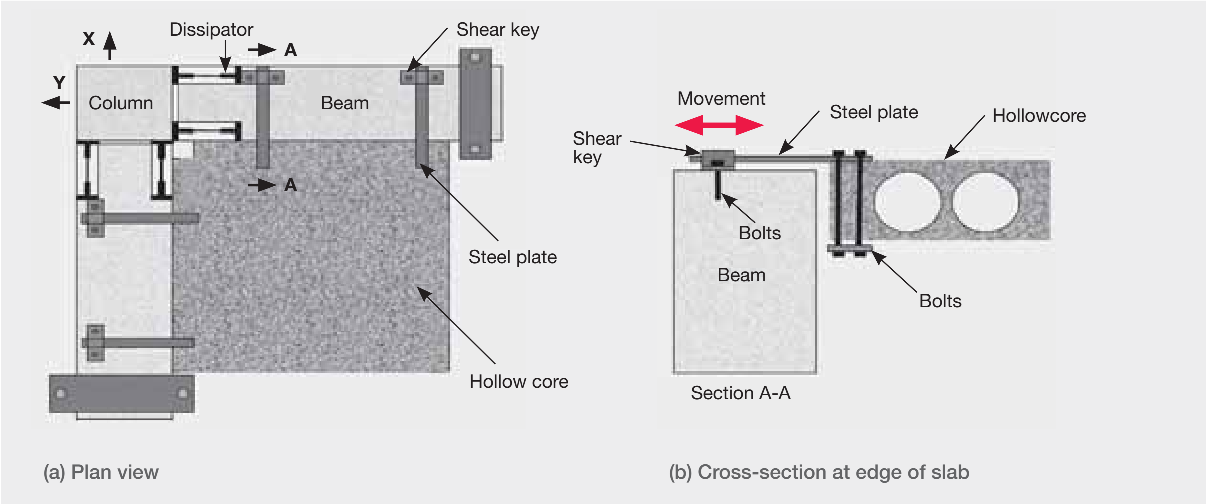


Figure 15: Beam-column joint with articulated floor unit at a corner of a reinforced concrete frame building (source: Amaris et al, 2007[12])

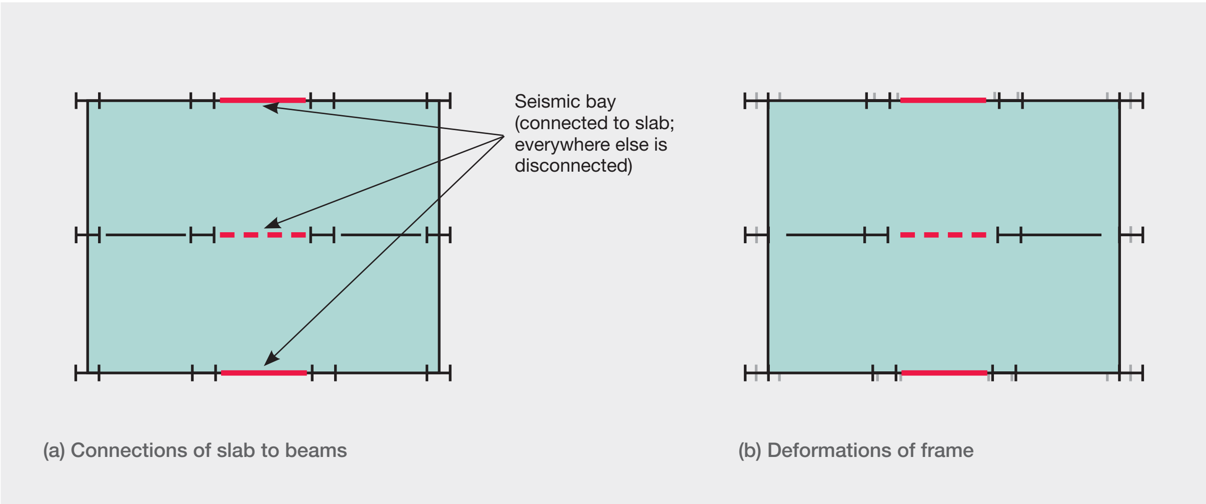


Figure 16: PRESSS technology with slab connected over one bay (source: Buchanan report)

Other ways to isolate floors include connecting the beams to the slab in one bay only, as shown in Figure 16, or by connecting the slab to gravity frames only and isolating the seismic resisting frame. We do not see how this proposal would work, as gapping between the columns and beams in the seismic bay would stretch the slab, which is continuous between the three bays. This stretching action would be likely to damage the slab.

(c) Frame elongation effects

Frame elongation occurs in traditional concrete frames as a result of the formation of plastic hinges, leading to slab damage and a reduced seating for precast floor elements. Post-tensioned rocking frames also suffer this detriment through the gapping that occurs at the beam-end-to-column-face joint.

The Buchanan report explains that for PRESSS (and traditional) frames, as the number of bays increases, so the outward displacement of the end columns increases owing to aggregation of gap opening. When this sway is superimposed with beam elongation, the columns end up being pushed apart in different ways. This cannot cause a column sway mechanism to form but it can increase the curvature imposed on columns.

The beams in a frame are subjected to axial compression or tension forces as the frame is displaced laterally. Designers need to be aware of this behaviour, as standard structural analysis packages do not predict elongation actions.

(d) Non-structural components

Low-damage building technology has been developed to minimise structural damage and is not directly concerned with non-structural components. It works by permitting displacements (which may be large) without structural damage. Therefore, careful detailing is required for non-structural elements (for example, cladding and ceiling systems, mechanical services) so that they can sustain seismic movements. As the structural engineer sometimes is not directly involved in the fit out of a building, it is important that architects and other relevant parties collaborate to ensure that a resilient system is provided.

3.3.2 Applications in reinforced concrete buildings

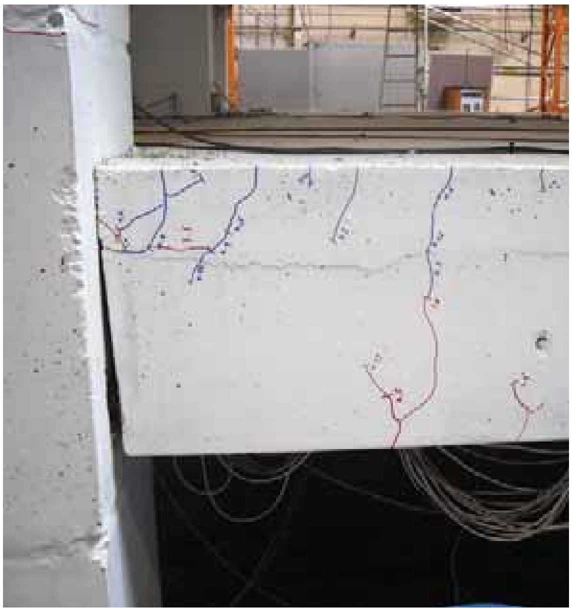
3.3.2.1 Background

The development of capacity design from the late 1960s to the early 1980s means that many reinforced concrete structures built before the 1980s do not have the necessary steel reinforcement detailing to give toughness and resilience in a major earthquake. The development of capacity design was an essential step in the design of ductile buildings. Professor Bull noted in his evidence that in the post-1980s era, the common way to prevent collapse was to make the building ductile by confining plastic deformation to specially detailed areas, which are referred to as potential plastic hinges. He observed that the problem with plastic hinges, particularly in concrete, is they can be significantly damaged in an earthquake, and they induce elongation. The engineering profession may have thought that these plastic hinges could be repaired, but Professor Bull stated that following laboratory work and in-field observations after the February earthquake, they were typically found to be beyond repair.

The advantage of PRESSS and slotted beam systems is that they suppress the formation of plastic hinges in structural members, dissipating the earthquake's energy in ductile jointed connections. Professor Pampanin described a PRESSS frame or wall system as consisting of precast concrete elements joined together with unbonded post-tensioning tendons or steel bars, creating a moment resisting structure. Under wind loading and low seismic actions, the clamping action of the post-tensioned bars guarantees strength similar to a typical cast in situ solution, whereas in a major earthquake, a rocking motion is initiated. Structural elements can be prefabricated off-site with high quality control and then assembled quickly and efficiently at the building site. Professor Pampanin also stated that by draping the tendon along the beam, longer span lengths may be achieved.

Steel or fibre-reinforced polymer armouring of the jointed regions between the precast units was used in the Southern Cross Hospital Endoscopy building (see Figure 19(d)) to suppress spalling of cover concrete at the joints.

Professor Bull reported that a slotted beam or non-tearing floor system was also developed as part of the PRESSS programme. By pivoting the beam about its top edge, gapping was limited to one side of the beam, which reduced damage to concrete floor slabs. Figure 17 shows laboratory testing of a two-storey slotted beam frame at the University of Canterbury. The two per cent drift imposed is at an ultimate limit state (ULS) level. Professor Bull described the damage in the beam and floor as only hairline cracking, whereas a conventional connection would typically have a significant accumulation of damage for the same level of imposed drift.



(a) Beam-column joint

(b) Concrete floor

Figure 17: Slotted beam laboratory testing at ultimate limit state (source: Desmond Bull)

The bottom longitudinal reinforcing bars are partially debonded in the beam close to the slot to avoid premature rupture of the steel. Professor Bull described testing two methods of debonding, namely a steel sleeve and a plastic tube. The steel sleeve performed better, as it provided superior restraint against buckling. Further design considerations include:

- treatment of steel reinforcing across the joint, to reduce its exposure to the environment;
- measures to prevent gaps being filled over the design life of the building, as people may not recognise the significance of the gaps; and
- repair or replacement of steel that has undergone repeated plastic cycles in one or more earthquakes.

Professor Bull described the slotted beam as a higher-performance system as the floor slabs remain intact. However, the replacement of the yielded steel reinforcing is an issue and the building may still not be repairable. This is the same issue as with conventional systems that form plastic hinges. External devices that can be replaced were discussed as a possible solution to this problem.

We note Professor Bull's opinion that the PRESSS and slotted beam concepts have the advantage of employing current building techniques and will therefore not require significant learning or special tools for builders. The key changes are in the design and detailing of joints, which will give a better performance at a cost that is competitive with conventional systems.

We agree that the concept has merit but further consideration of the three points raised above is required.

3.3.2.2 Practical examples

1. Alan MacDiarmid building

The first multi-storey PRESSS building constructed in New Zealand was the Alan MacDiarmid building at Victoria University of Wellington (see Figure 18(a)), completed in 2009. Mr Alistair Cattanach, a director of Dunning Thornton Consultants Ltd who designed the building, has advised the Royal Commission about the project.

The project budget was $40 million (though a sixth of this cost was associated with structure required specifically for the laboratory). The building has two basement levels, which are conventionally constructed. Above this is a four-storey PRESSS building with an area of 6000m^2 for teaching and research laboratories.

The structural system consists of post-tensioned seismic frames in one direction, and coupled post-tensioned walls in the other direction. This building features external replaceable supplemental dampers at the moment resisting frame joints (see Figure 18(b)) and slender steel coupling beams between rocking walls, which yield in flexure (see Figure 18(c)).

Key benefits demonstrated by this project include:

1. In a major earthquake, the rocking is initiated, which increases the system's period of vibration. This reduces building accelerations and damage to sensitive equipment.
2. The ductile rocking joints suppress structural damage.
3. The rocking system is very stiff, with minimal displacements during small earthquakes.
4. Increased site safety, better quality assurance and speed of construction.

Challenges that needed to be confronted include:

1. Designing and detailing the floor and its connections to the walls and frames. This requires extensive work and expertise.
2. Anchorage zones for post-tensioned tendons take up space and affect building geometry.
3. Owing to constraints on lifting equipment, a sandwich wall system was used, but this system was quite complex.
4. A thorough review process was required. This included a peer review by Professor Pampanin and a scope review of concepts by Professor Priestley.

In 2009 the building was awarded the New Zealand Concrete Society Supreme Award in recognition of its innovation and advancement of concrete practice in design, construction and research.

(a) Finished building

(b) Beam-column connection detail during construction

(c) Steel coupling beam

Figure 18: PRESSS technology in the Alan MacDiarmid building, Wellington (source: Alistair Cattanach)

2. Southern Cross Hospital Endoscopy building

Mr Gary Haverland, Director of Structex Metro Ltd, described the key details of the second PRESSS building constructed in New Zealand. This is the Southern Cross Hospital Endoscopy building, shown in Figure 19(a), which was completed a month before the September earthquake and is located just north of the Christchurch CBD.

The four-storey building was designed as an Importance Level 3 structure that required piled foundations because of the site's soft soils. The gross floor area was 2940m^2. The cost was \$2450 per m^2.

This structure has both frames (Figure 19(b)) and coupled walls, which resist lateral forces in the two orthogonal directions. The unbonded post-tensioned walls are coupled by using U-shaped flexural plate dissipaters, details of which are shown in Figure 19(c).

(a) Architect's impression

(b) PRESSS frame under construction

(c) U-shaped flexural plates between coupled walls

(d) Steel armoured beam-column joint

Figure 19: Southern Cross Hospital Endoscopy building (source: Gary Haverland)

Some advantages of using a PRESSS structure in this development were identified by Mr Haverland. These included:

1. There are no plastic hinges so there is little structural damage. The reduction in potential downtime was important for the client.
2. The building structure is self-centring, resulting in little residual lean after an earthquake.
3. Lower design seismic actions compared to a conventional reinforced concrete frame or wall building. This means less risk of damage to contents, lower wall reinforcement and foundation forces. This was important because of the expensive medical equipment in the building.
4. Less in situ concrete on site, meaning shorter construction time. Construction also used conventional building components.

Mr Haverland described the building as having satisfactorily passed the tests of the Canterbury earthquakes, with the seismic resisting structure (frame and walls) performing "extremely well". The building suffered minor cosmetic damage to non-structural components, with some damage to services requiring repair. After minimal downtime, the building was made fully operational again.

Mr Haverland commented that steel armoured joints had performed well (see Figure 19(d)) and he recommended this approach to reduce spalling in future buildings.

An initial cost of a conventional building was estimated to be $7.2 million. The PRESSS building was constructed for $6.9 million but other problems encountered, including upgrading the boiler, running additional services and striking a well in the excavation for the lift pit, brought it back up to the initial budget of $7.2 million. The structural elements cost $2.17 million, around 30 per cent of the total building cost, which in Mr Haverland's view is comparable to other conventional buildings.

3.3.3 Applications in steel buildings

3.3.3.1 Background

Multi-storey steel building construction has grown in prominence over the last 20 years. The lull before this time was reported by Clifton et al[13] to be due to the 1970s labour disputes that adversely affected the steel industry, as well as the recession in the late 1980s.

The number of steel buildings in the Christchurch CBD is relatively low compared to concrete buildings. These steel buildings date from 1985 to 2010, and therefore were designed to modern seismic specifications. Professor Charles Clifton told the Royal Commission that these structural systems performed well, satisfying their life-safety objective, with some buildings also being able to be reoccupied after repairs.

3.3.3.2 Low-damage steel building technologies

Conventional lateral resisting systems used in steel buildings include the moment resisting frame (MRF), the eccentrically braced frame (EBF) and the concentrically braced frame (CBF). The new concepts used to reduce damage in structural steel incorporate these forms of lateral resisting systems. However, there is a focus on special detailing in regions where structural elements are expected to be damaged.

(a) Technologies in moment resisting frame structures

The sliding hinge joint has been tested and developed in New Zealand by Professors Charles Clifton and Gregory MacRae. This system has been used in five multi-storey buildings to date. It is only recommended for dry internal environments, as the long-term durability and maintenance of the sliding joints is a subject of ongoing research.

In a severe earthquake, the column sways back and forth and the beam rotates about its top flange, while the bottom components undergo controlled sliding. The friction force is derived from the clamped plates sliding relative to each other. This behaviour gives good energy absorption and suppresses damage in the column and beam. Figure 20 shows some of the key aspects of this concept.

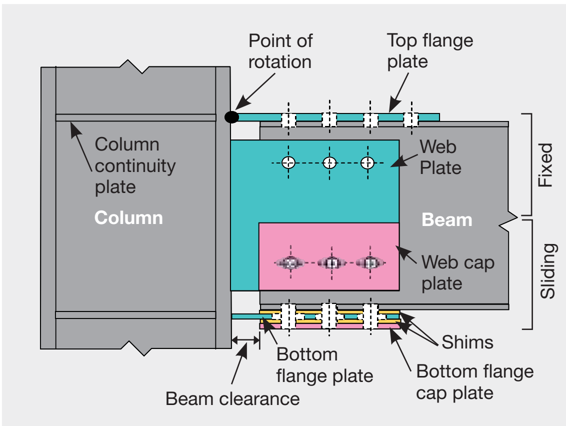


Figure 20: Sliding hinge joint detailing (source: Buchanan report)

Professor Clifton described further desirable characteristics of this system as follows:

1. Large deformations can be sustained using elongated boltholes and the clearance between the end of the beam and the column.
2. Strength and stiffness are decoupled. Since most member sizes are governed by stiffness, the lower strength of this connection is not disadvantageous as the friction connection has high stiffness.
3. Strength can be controlled by the number and size of friction grip bolts.

The system is still evolving, with different arrangements to reduce the localised bending in plates. To increase the ability of the connection to self-centre, a double-acting ring spring can be connected to the underside of the beam's flange and to the column face.

Professor Clifton stated that the construction detailing is similar to conventional connections. Damage is suppressed in composite floors, beams and columns with damaged bolts being replaced or re-tightened after a major earthquake. He estimated that the cost would be one to five per cent greater than that of a conventional system.

Other devices applicable to steel moment frames include the high-force-to-volume (HF2V) dissipater, which could replace the sliding friction joints. Professor Clifton also described the flange-bolted joint, which he considered suitable only for low-seismicity regions such as Auckland.

Rocking structures have been adopted in steel structures, such as the uplifting columns used in the Te Puni Student Village (see page 29). Some issues to be considered when contemplating the use of rocking structures were referred to in the Buchanan report, including:

1. Vertical impacts on the foundation.
2. Horizontal accelerations resulting from impact. Some systems will have a rapid increase in stiffness when travelling at high velocity, which may produce uncomfortable shock in the building.
3. Vertical deformations on the side of the frame may result in large demands to the floor slab as the wall lifts up the floors.

Professor Clifton described another concept, the linked-column frame, which consists of two closely spaced columns with links between them acting as the primary lateral load resisting system. This is coupled with a linked gravity frame. The gravity frames are more flexible and are designed to remain elastic, helping the building to self-centre. A conceptual example from research carried out at the University of Portland, Oregon, is shown in Figure 21.

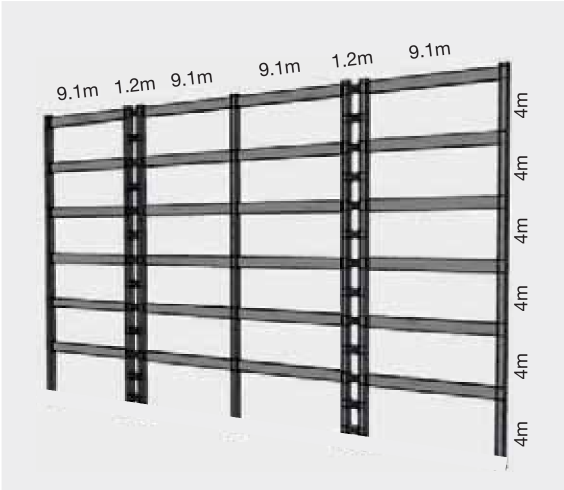


Figure 21: Linked-column frame (source: Charles Clifton)

The links in the frame are intended to yield and can be replaced after an earthquake. The system has a high level of redundancy, with frames remaining stable after removal of damaged links. These replaceable links can be bolted active links (similar to those used in EBFs) or could incorporate the sliding hinge joint. The technology is readily applicable to standard capacity design principles.

(b) Technologies in braced frame structures

Bolted replaceable active links

The bolted replaceable link described by Professor Clifton has an advantage over the conventional EBF of an easy link replacement. The performance of EBFs during the Christchurch earthquakes has shown that the floor slab may contribute to the strength of the links, reducing deformations and hence reducing damage. Investigations to quantify slab strength, stiffness and over-strength effects on the EBFs are currently under way at The University of Auckland. Figure 22 shows how this replaceable link may be constructed. This is still in development, with load tracking being an important consideration in the detailing of steel connections.

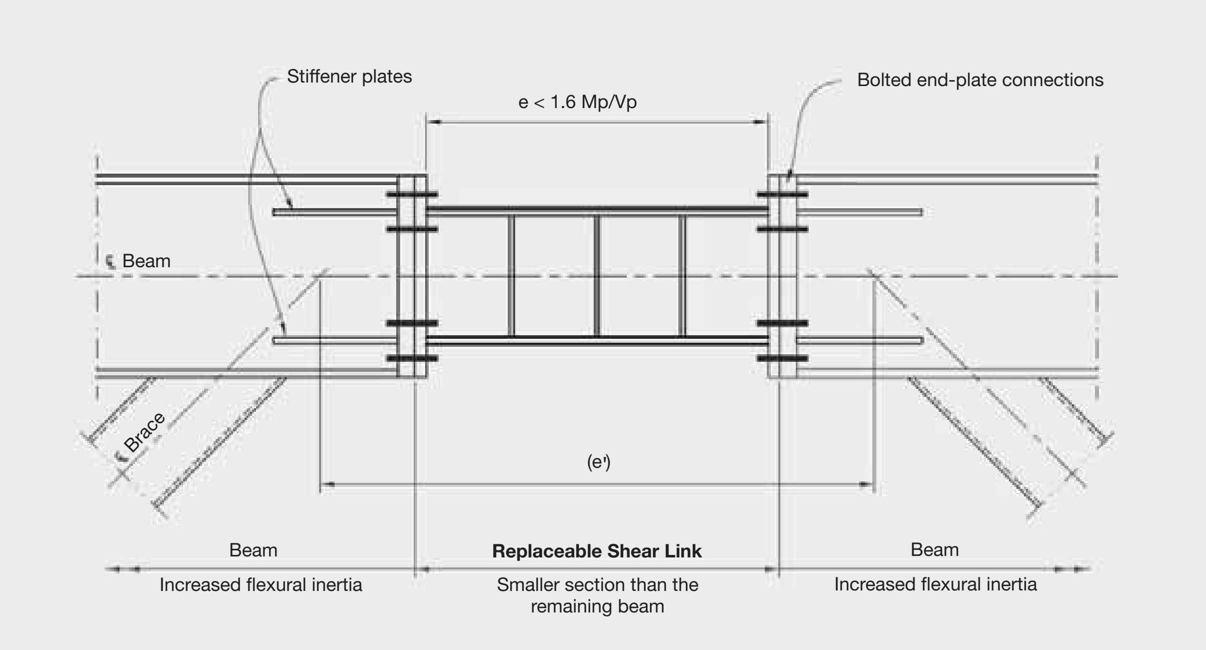


Figure 22: Bolted replaceable link in an eccentrically braced frame (EBF) (source: Buchanan report)

Concentrically braced frames

In concentrically braced frames, supplemental damping devices such as the buckling restrained brace and the friction sliding brace can be incorporated into conventional systems. In a conventional concentric frame, the braces yield in tension and buckle in compression, which leads to slackening in the system.

3.3.3.3 Practical example: Te Puni Student Village

Low-damage technologies were used in the Te Puni Student Village buildings after a request from Victoria University of Wellington to develop a design that would limit damage in a major earthquake. Mr Sean Gledhill, Technical Director of Aurecon, gave evidence to the Royal Commission on the practical application of low-damage steel devices in this development.

The project involved the construction of three 11-storey buildings (see Figure 23(a)). A conventional design was tendered in parallel with the low-damage design solution. Mr Gledhill said the drivers leading to the selection of the low-damage design were:

- provision of a facility to function as a disaster administration centre with nominal repair after a major earthquake;
- suitability to multi-storey steel buildings;
- speed and ease of construction (see Figure 23(b));
- sustainability for the future; and
- economy of mitigation of damage to primary structural members.

In collaboration with the latest research available from The University of Auckland and the Heavy Engineering Research Association (HERA), a lateral load resisting system of moment frames with sliding friction hinge joints (Figure 23(c)) was combined with concentrically braced rocking steel frames. The rocking motion from uplifting columns was controlled with Ringfeder springs and friction plates (Figure 23(d)). These details dissipate earthquake energy and suppress damage to structural components.

In terms of cost-effectiveness, Mr Gledhill said the low-damage technologies cost an additional one to four per cent of capital costs compared to the conventional design. He outlined some other costs incurred on the project, including the additional design effort and a more rigorous consenting process.

(a) Completed buildings

(b) Building under construction

(c) Sliding hinge joints in a moment resisting frame

(d) Rocking column detail

Figure 23: Te Puni Student Village, Wellington (source: Sean Gledhill)

3.3.4 Applications in timber buildings

3.3.4.1 Background

Many of the technologies discussed in preceding sections, such as the PRESSS technology, can be adapted into highly engineered wood structural systems.

The 1855 Wairarapa earthquake showed that timber buildings behaved well in earthquakes. Lessons from this led to the construction of the old Government Buildings (now functioning as the Law School of Victoria University) in 1876, a large timber structure with a facade textured to look like stone, as shown in Figure 24.

Figure 24: Old Government Buildings, Wellington (source: Andrew Buchanan)

An important difference between wood and steel or concrete is that wood is a highly inhomogeneous material, with different strength, stiffness and shrinking-swelling characteristics parallel or perpendicular to the direction of the grain. Professor Buchanan described wood as being like a bundle of drinking straws that transport water up the structure, with the highest strength in the direction parallel to the grain.

Timber is a lightweight, flexible (low elastic modulus) and brittle material. Professor Buchanan noted that the latest wood materials include plywood, laminated veneer lumber (LVL), Glulam (Glue Laminated) and cross laminated timber (CLT)). These engineered wood products lessen the inherent variability of wood by peeling or sawing it into layers and gluing them back together in alternating patterns. Since timber is brittle, it is combined with steel fasteners or connections to provide ductility and energy dissipation in an earthquake.

Since 2004, low-damage design has been implemented in timber structures. Particular attention has been paid to the hybrid connections, which combine post-tensioning bars with internal or external steel dissipaters. The structural concept described by Professor Buchanan is that seismic movements are accommodated through a controlled rocking mechanism between prefabricated elements. The structural elements are held together by long unbonded high-strength steel tendons. Energy dissipation is provided by the yielding of short lengths of replaceable mild steel or by energy-dissipation devices.

The rocking timber system has been named Pres-Lam and it covers both seismic resistant frames and walls. Professor Buchanan explained that the system has been designed and developed at the University of Canterbury[14] with the support of the Structural Timber Innovation Company Ltd (STIC), a research consortium of the timber industry, universities and government. STIC is marketing Pres-Lam and other new timber technologies under the trade name EXPAN.

The development of multi-storey Pres-Lam timber buildings has been the focus of a major research programme at the University of Canterbury for the past five years, in association with The University of Auckland and the University of Technology, Sydney. Figure 25 shows testing on a two-thirds-scale multi-storey frame and wall building. After extensive testing with no significant structural damage, this test building was dismantled and re-erected as the head office of STIC on the University of Canterbury campus.

Professor Buchanan said that like most other materials, post-tensioned timber under high compressive stresses experiences some axial shortening caused by creep and relaxation, similar to concrete, in the direction parallel to the grain. The associated losses in post-tensioning are allowed for in design. Perpendicular to the grain the stiffness is much less and the creep and shrinkage are very much greater than along the grain. The poor properties perpendicular to the grain mean that columns in post-tensioned beam-column joints require special reinforcement.

Figure 25: Multi-storey timber building tested at the University of Canterbury (source: Andrew Buchanan)

Multi-storey timber buildings are also being constructed in other parts of the world. Professor Buchanan described a seven-storey timber building that was prefabricated in Italy and then shipped to Japan, where it was tested on the largest shake-table in the world, as shown in Figure 26. This building is made of CLT wood panels. It is not post-tensioned, but the panels are well connected with metal fasteners and there was sufficient gravity load to ensure self-centring. Professor Buchanan said the building survived a number of very large earthquake motions with no significant structural damage, but the floor accelerations at the top of the building were high. He indicated that these accelerations could have been reduced if the building was designed for sufficient energy dissipation or ductility.

Figure 26: Shake-table testing of a seven-storey CLT building in Japan (source: National Research Council of Italy – Trees and Timber Institute (IVALSA))

Dr Pierre Quenneville from The University of Auckland gave evidence on the performance and details of steel slip-friction connections. The advantages and limitations are similar to those outlined in the discussion on supplemental damping devices, such as improved energy dissipation, self-centering ability and durability issues.

Mr Mark Batchelar, Principal of MLB Consulting Engineers, described further benefits of timber structures. He said that they usually have an inherent strength reserve and resilience, as deflection considerations typically govern the size of structural members rather than the strength requirements. The reduced weight of timber gives a reduced seismic demand and can lead to a significant reduction in foundation costs on poor soil sites compared to concrete buildings.

Mr Batchelar also described the concept of using hollow timber piles. The Royal Commission acknowledges the merits of this, which will need further development and testing in the Canterbury alluvial soils. It has practical advantages for use in foundations of light structures.

Professor Buchanan described timber as requiring unique consideration with regard to durability, decay and dimensional stability, all of which require it to be kept dry. Timber buildings also need special attention for fire safety and acoustics. Timber technologies are relatively new compared to the corresponding alternatives in steel and concrete, and there is a lot of work currently under way to ensure that the products are properly tested before they are widely adopted.

3.3.4.2 Practical example: Nelson Marlborough Institute of Technology (NMIT) building

The first ever practical application of the Pres-Lam technology was in the Nelson Marlborough Institute of Technology (NMIT) Arts and Media facility in Nelson. Mr Carl Devereux, Technical Director of Aurecon, provided evidence to the Royal Commission about this building. The NMIT building is divided into three blocks that were opened in January 2011 (Figure 27(a)). The three-storey block incorporates damage-mitigation technologies and has a footprint of 500m^2.

This structure contains vertically post-tensioned coupled rocking timber walls, which resist lateral loads in both directions. These were prefabricated off-site and lifted into place to be connected at the foundations (Figure 27(b)). The walls are post-tensioned to the foundation through high-strength steel bars, with a cavity in the wall for the steel bar couplers.

Steel U-shaped flexural plates link the pairs of structural walls together and provide dissipative capacity to the system. Mr Devereux said that, based on Aurecon's current experience and knowledge, a building height of up to 10 storeys is achievable with this system.

All structural elements including the beams, columns, walls and floors are constructed of LVL, as shown in Figure 27(c). LVL is a sustainable building product that is grown and manufactured locally.

Through a cost analysis, Mr Devereux estimated the primary structure to be 33 per cent of the total capital cost. The steel and concrete structure options were also considered and cost around 30 to 40 per cent of the total capital cost. This showed that the cost of this new low-damage technology is comparable to conventional systems and therefore does not have a significant effect on the total capital cost.

(a) Finished building

(b) Installation of prefabricated wall elements

(c) During construction

Figure 27: Nelson Marlborough Institute of Technology (NMIT) building in Nelson (source: Carl Devereux)

Section 4: Professional and regulatory implementation

4.1 Department of Building and Housing (DBH)

At present the low-damage technologies discussed in this Report are not provided for in the Building Code as prescribed "acceptable solutions" or "verification methods", and there are no New Zealand Standards that specifically provide for them. This means that their use is dependent on specific approvals given for each proposal in the building consent process, where they can be advanced as an alternative solution to meeting the performance requirements of the Building Code. While the Building Act allows the low-damage technologies to be used, the consent process is inevitably more expensive than for buildings of conventional design, and depends not only on detailed building consent applications that demonstrate the robustness of the technology, but also on a receptive and educated response from the individual building consent authority. The desirability of a more encouraging regulatory environment was an issue addressed in the hearing by Mr David Kelly and Mr Peter Thorby of DBH. This is a matter to which we will return in a later part of our Report, where it can form part of our overall discussion of the way in which the building consent process is designed and implemented.

4.2 Architects' perspective

Aesthetics and architectural requirements are key factors contributing to the form of a structural system in a building.

Associate Professor Andrew Charleson from the School of Architecture at Victoria University of Wellington, and Trevor Watt, director of Athfield Architects in Christchurch, gave evidence to the Royal Commission on how the low-damage building technologies may affect current practice. Both agreed that the introduction of these types of structures into mainstream design and construction practices would have few significant architectural implications, as the forms of structure are very similar.

Base isolation was discussed as the technology that is most demanding on architectural features, as all entrances, services and other fittings that cross the seismic gap (or isolation plane) have to be specifically detailed to accommodate seismic movement.

Associate Professor Charleson explained that one disadvantage of using new technologies is that they may require more maintenance. He considered that there should be regular checks on each use of the emerging technologies and gave the example of a base-isolated building where the whole system had been compromised because of a new addition to the building.

In the case of the PRESSS used for the Southern Cross Hospital Endoscopy building, both conventional reinforced concrete and PRESSS solutions were considered. It was Mr Haverland's evidence that the use of the low-damage technology had no effect on architectural layout, with no reduction in the available floor area.

The Nelson Marlborough Institute of Technology (NMIT) building constructed using the latest timber Pres-Lam technology is shown in Figure 28. Mr Watt explained that aesthetics was an important component, and the architect wished to expose the structure and the damping devices. This is quite a different aesthetic, but in the Christchurch context, Mr Watt expected that a much wider range of building aesthetics would be used for new buildings.

Figure 28: Architectural finish, NMIT building (source: Trevor Watt)

Damage caused by earthquakes also occurs to non-structural elements. Frequently these elements are included in the architect's design. To prevent or limit the amount of secondary damage, engineers and architects should collaborate to minimise the potential distortion applied to non-structural elements. Particular attention must be paid to prevent the failure of non-structural elements blocking egress routes.

Section 5: Cost considerations

Evidence presented to the Royal Commission demonstrated that low-damage technologies are comparable in cost to conventional construction. Professor Pampanin considered the costs to be similar to or only slightly higher than traditional methods. The extra costs would likely be offset by the improved performance of the building and other benefits such as a shorter construction time. The small number of examples that the Royal Commission has been able to consider has not enabled us to confirm Professor Pampanin's views. However, on the evidence we heard, discussed above, it does appear that the increased cost of low-damage technologies ought not to be seen as prohibitive when compared with the possible benefits, especially for long-term owners.

5.1 Methods of controlling seismic response: base isolation

Ms Devine gave evidence to the Royal Commission on the business case for seismic isolation, and specifically the question of cost.

For new construction, Ms Devine stated that a general rule of thumb is that the inclusion of all aspects of seismic isolation will add no more than three per cent to the construction cost. A feature of base isolation is to trade off the increased initial cost for a decreased lifetime cost. The reduced accelerations achieved by isolation are the best way to protect contents and non-structural elements. A seismically isolated building has good potential to remain fully functional after an earthquake event, eliminating or minimising losses caused by downtime, lost production, lost data and lost building contents.

Base isolation can be used as a retrofit technique for existing buildings, but the variables inherent in modifying structures make it difficult to give a meaningful indication of cost.

5.2 Low-damage technologies

Evidence given at the hearings was in general agreement that the use of low-damage technologies, such as PRESSS or sliding friction dampers, results in only a small cost increase compared to conventional methods. The Southern Cross Hospital Endoscopy building and Nelson Marlborough Institute of Technology (NMIT) building, which use the PRESSS and Pres-Lam systems respectively, were found to be comparable in cost to conventional reinforced concrete and/or steel alternatives. The Te Puni Student Village, built using the latest steel technologies, had increased costs in the range of one to four per cent of the total construction cost.

Professor Pampanin advanced the following propositions on the relevant cost considerations for low-damage technologies:

1. Overall the cost is comparable to the use of their conventional counterparts.
2. The more they are developed and constructed, the more they can result in less expensive yet higher performance solutions.
3. The material costs are about the same as in conventional solutions (that is, post-tensioned costs are balanced by more efficient use of materials), with faster erection time.
4. In first applications, the novelty of the system and lack of comparison to previous cases may lead to a higher prediction of costs.

5.3 Other considerations

Mr Hare provided a breakdown of costs for a typical 6 to 15 storey office building from Rawlinson,[15] the standard price guide used in the construction industry. The breakdown indicates that the structure represents typically only 21 per cent of the cost of the building, as shown in Figure 29. This means that if a low-damage technology requires, say, a five per cent increase in structure costs, that will only be a one per cent increase in the total cost.

Mr Hare made the point that if a building is so badly damaged that the structure is non-repairable it is a 100 per cent loss. But when looking at the building's performance in a lower-level earthquake (for example, the September earthquake), which may leave the structural elements in a reasonable state, it is still necessary to consider the damaged state of the other 79 per cent of the building value.

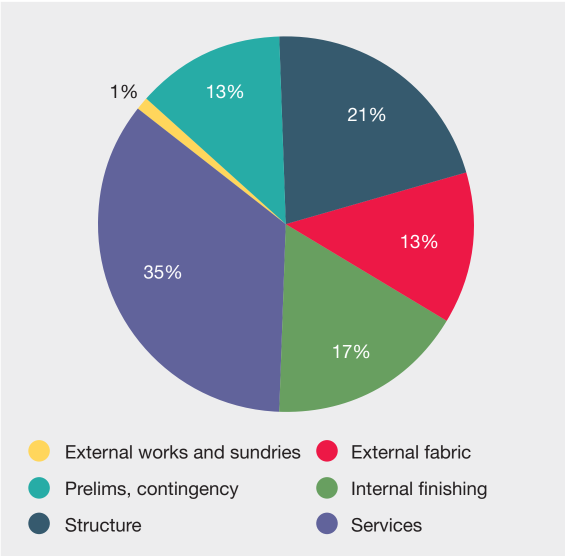


Figure 29: Rawlinson's[15] elemental cost of a typical 6 to 15 storey office building

Dr. Richard Sharpe gave evidence that "fix, fasten and forget" is a simple but effective way to lessen the non-structural and contents damage to a building. The September earthquake alone resulted in significant economic cost, with damage to partitions, ceilings, mechanical services and other non-structural elements requiring repair. Protecting the structural system from damage is only one aspect of damage mitigation.

Another interesting finding from examining Rawlinson[15] is that the cost of an office building does not necessarily correlate to the seismicity of the region. Wellington and Auckland have similar building cost ranges, despite the difference in their hazard factors (0.4 and 0.13 respectively). This shows that there are significant other considerations driving the overall cost of buildings.

Section 6: Discussion

The Royal Commission received submissions and heard evidence at hearings on the potential for alternative designs to reduce the social and economic costs arising from severe earthquakes.

The social and economic costs to Christchurch, Canterbury and New Zealand have been extreme and were unexpected by the public even for an event that created forces considerably greater than the design level. These costs include the time cost of business interruption.

It is relevant to consider the magnitude of these costs in the context of the rarity of the event. It is notable that the event that occurred on 4 September 2010 tested structures at around the design level. The structural damage to many well-designed modern buildings was not great. However, the possibility that alternative forms of structure could behave better in a major earthquake and sustain much less damage is attractive. Research into alternatives that perform safely with less damage in an extreme seismic event warrants support.

The various methods proposed and described in some detail above can be applied using conventional building materials and include a range of devices that absorb energy that would otherwise damage the building.

For low-damage structures, the initial capital cost was reported to the Royal Commission and examples of cost were provided. A modest increase of a few per cent was reported. Opinions were expressed that there is potential for the cost to fall as confidence grows in the techniques, and the prospect of rapid assembly of the structural frame saves construction time. In these respects, alternative technologies offer promise.

As research continues on low-damage buildings, matters have been identified that warrant attention. These include:

PRESSS and Pres-Lam structures:

- corrosion resistance of cables, particularly if exposed to moisture;
- stored energy in heavily stressed cables or rods if inadvertently released;
- need for additional redundancy if a cable failure occurs;
- ability to alter a building structure without losing its integrity; and
- desirability of redundancy of structural capacity.

Base-isolated structures:

- clearances around the structure to allow for movement;
- ensuring the space around the structure is not obstructed during the life of the building; and
- better understanding of ground conditions and the interaction between soils, foundations and building structure.

Devices:

- use of proven energy-dissipating devices; and
- standardisation of design practice for connections.

Building standards:

- development of standards that are incorporated into the building regulations;
- consideration of fire resistance for post-tensioned tendons;
- standardised methods of design; and
- familiarising building consent authorities, design organisations and constructors with low-damage techniques.

Communications:

- familiarising the public, owners and businesses with the potential of low-damage buildings; and
- commercial implications, funding and insurance are possible areas of interest.

Increasing the use of timber, a locally produced and plentiful material, has important economic advantages for New Zealand. Durability has been established through the use of preservatives. The manufacture of LVL and Glulam enables long lengths to be used with known material properties. An innovative application of treated timber piles (which are already widely used) uses a hole cored down the centre of the pile to allow jetting and subsequent introduction of cement grout to the pile base. The Royal Commission endorses these innovative developments.

The Royal Commission acknowledges the role these innovations can have and notes that there has already been considerable progress made at Canterbury and Auckland universities and in some design offices. Buildings that use low-damage technologies also offer prospects for ease of repair. Replacement of connections, energy-dissipating devices and localised elements of structure are ways in which buildings can be restored to full strength after a major earthquake. The potential for these benefits was apparent from presentations to the Commission.

Section 7: Conclusions and recommendations

7.1 Conclusions

In considering the use of low-damage technologies as an alternative to current building methods, it is important that the lifetime costs be considered, including the capital cost, maintenance costs, the difference in performance in earthquakes and the resulting differences in repair costs and downtime of the building.

It is also important that all owners during the life of the building should be aware of the structural system. If an owner in the future wishes to modify a building, it is essential that they should understand the implications. Many low-damage buildings rely on different structural solutions than those of conventional buildings. Alterations may compromise the building's behaviour in earthquakes. Examples of matters of concern have been highlighted in the discussion.

In selecting an appropriate low-damage technology, it is important to realise that these innovative techniques are in a relatively early stage of development. Some questions of a practical nature are being addressed as these methods become more widely adopted.

From the evidence we have received, we consider that there is a place for the use of new building techniques in the rebuild of Christchurch and in developments elsewhere. There will be many cases where their use is justified because of better structural performance not withstanding any increased costs that result.

7.2 Recommendations

Recommendations

We recommend that:

66. Research should continue into the development of low-damage technologies.
67. The Department of Building and Housing should work with researchers, engineering design specialists and industry product providers to ensure evidence-based information is easily available to designers and building consent authorities to enable low-damage technologies to proceed more readily through the building consent process as alternative solutions.
68. The Department of Building and Housing should work with researchers, engineering design specialists and industry product providers to progress, over time, the more developed low-damage technologies through to citation in the Building Code as acceptable solutions or verification methods. This may involve further development of existing cited Standards for materials, devices and methods of analysis.
69. The Department of Building and Housing should foster greater communication and knowledge of the development of these low-damage technologies among building owners, designers, building consent authorities and the public.
70. To prevent or limit the amount of secondary damage, engineers and architects should collaborate to minimise the potential distortion applied to non-structural elements. Particular attention must be paid to prevent the failure of non-structural elements blocking egress routes.

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Royal Commission

PO Box 14053
Christchurch Mail Centre 8544
Christchurch
New Zealand
0800 337 468
+64 3 741 3000
canterbury@royalcommission.govt.nz