

DRIVERS AND CHALLENGES IN USING LOW DAMAGE SEISMIC DESIGNS IN CHRISTCHURCH BUILDINGS

Juliet Skidmore¹, Gabriele Granello² and Alessandro Palermo³

(Submitted April 2021; Reviewed June 2021; Accepted April 2022)

ABSTRACT

Following the extensive damage to Christchurch's infrastructure in the 2010 and 2011 Canterbury earthquakes, a complete rebuild of the city centre has been undertaken, with a particular focus on seismic-resilient buildings. This paper explores the application of different seismic-resilient technologies to buildings in Christchurch, by interviewing the structural engineers responsible for the design of six case study structures. Focus is given to the structural performance and benefits of each technology, and the key factors driving the clients' and engineers' decision to use the system. Comparisons are then made between resilient technologies, looking at the relative construction times and cost, areas of difficulty in design and construction, and the expected performance. Assessments are made of the knowledgeability of stakeholders, including clients and engineers, in resilient design, and the aspects that need to be addressed in the ongoing research and development of new and existing resilient technologies.

Results show that the main factors identified driving clients' and engineers' decisions to use a seismic-resilient design were the structural performance, ease of construction and publicity. Key issues that need to be addressed during the development of new resilient systems are the durability, constructability and cost of a design, in addition to the production of design and construction aids, to both support engineers and contractors in the process, and encourage them to undertake a seismic-resilient design. Ideas are presented for increasing client and public awareness of different resilient systems available so that the demand and commission for seismic-resilient buildings in the city may increase.

INTRODUCTION

Following the Canterbury earthquakes in 2010 and 2011 [1], the city of Christchurch suffered significant damage with many of the city's buildings undergoing large irreversible displacements or collapse [2], causing a 10% GDP loss on the New Zealand economy [3]. In the ten years after such events, Christchurch has undergone a large-scale rebuild of its city, with particular attention being paid to low damage designs which would prevent such widespread damage occurring again [4-7]. As a result, Christchurch has become one of the leading locations for the research and development of low damage buildings in the world [8].

When commissioning for a new building however, there are many factors which influence whether a low damage design will be chosen over a traditional design, and if used, which seismic-resilient technology will be adopted. For instance, the designer might choose to prioritise construction cost over the seismic performance of a building. Furthermore, there are several stakeholders who influence these decisions, such as clients and engineers, who often have different priorities in design.

To further advance the widespread use of low damage technologies, this paper explores the key factors influencing stakeholders' decisions to adopt or not adopt a low damage design in a specific project, and their subsequent choice of resilient technology.

Specific study into the most important aspects to each of the clients, engineers and tenants is undertaken. In addition, the other factors which are less considered during the selection process, but have a large influence on the construction time and

ease of design, such as availability of design guidelines, are explored. By assessing these aspects, we can identify the issues that need to be addressed in the ongoing research and development of resilient technologies to meet the demands of stakeholders, and make them more willing to take on a resistant design, in addition to increasing the efficiency of the design process. From this, exploration into the methods of popularising low damage design among engineers, clients and the general public can be conducted.

Within this framework, six low damage technologies are discussed in this paper, namely buckling-restrained braces [9-11], viscous dampers [12-15], steel rocking frames and walls [16-19], PREcast seismic structural systems, also known as PRESSS (concrete rocking) [20-22], prestressed-laminated timber (timber rocking) [23,24] and base isolation [12,25-27].

First, each technology is briefly presented from a conceptual point of view, highlighting its main features and peculiarities. Then, specific case study projects representative of the technology are presented from the point of view of the design engineers involved. Within this process, the major key drivers for the realization of each project are explored. Finally, data are compared and correlated, offering a global overview of the mechanisms leading to, and involved in, the design of low damage structures.

Methodology

To obtain information about the mechanisms leading to the realization of a low damage building, a survey with New Zealand structural engineers was undertaken in 2019.

¹ Corresponding Author, Structural Engineer, Price & Myers, London, United Kingdom, jskidmore@pricemyers.com

² Research Associate, University of Edinburgh, United Kingdom, ggranell@ed.ac.uk (Member)

³ Professor, Department of Civil Engineering and Natural Resources, University of Canterbury, New Zealand, Alessandro.palermo@canterbury.ac.nz (Fellow)

Six main projects in Christchurch (one for each technology) were selected as case studies:

- PwC Centre Building (-43.533052, 172.632403) (Case study 1) as an example of buckling restrained braces [28].
- Rehua Building (-43.523035, 172.584467) (Case Study 2) as an example of viscous dampers [29].
- Tūranga Library (-43.529811, 172.637182) (Case study 3) as an example of concrete rocking walls and steel moment resisting frames with rocking column base connections [30].
- Southern Cross Hospital (-43.520038, 172.635096) (Case study 4) as an example of a PREcast seismic structural system; i.e. PRESSS (concrete rocking structure) [31].
- Beatrice Tinsley Building (-43.522556, 172.583101) (Case Study 5) as an example of Pres-Lam technology (timber rocking structure) [32].
- Justice and Emergency Service Precinct (-43.534451, 172.634187) (Case study 6) as an example of base isolation [33,34].

Questions focused on both the general and detailed aspects of low damage building projects including cost, and the priorities of the different stakeholders involved. The following five stakeholders were identified and used as subjects in the comparative sections:

- Clients, who commissioned for the building.
- Architects, who proposed an architectural design for the building.
- Engineers, who were involved in designing the building and technology.
- Contractors, who constructed the building.
- Tenants, who are the eventual occupier of the building.

To obtain comparable answers between questionnaires, questions were either multiple-choice, where additional options were added by interviewees when necessary during the interview, or ranked as percentages, which allowed for a broad range of answers and more specific results to be obtained.

Although it would certainly have been valuable to interview all the stakeholders involved in each project, the interviews were limited to the structural engineers to focus on their perspective as a consistent group.

LOW DAMAGE TECHNOLOGIES CURRENTLY IN USE IN CHRISTCHURCH

PwC Centre Building: Example of Buckling-Restrained Braces (BRBs)

Following the 2011 Canterbury earthquake, buckling-restrained braces (BRBs) have been adopted in several buildings in Christchurch.

BRBs consist of four sections (see Figure 1): an inner steel core; filler material; unbonding material; and an outer steel tube [9]. The steel core is the main load-bearing member and is designed to carry axial loads without buckling. A filler material, comprised of mortar or infill concrete, is located between the core and outer tube to resist buckling stress. An unbonding material lies between the core and filler material to reduce friction and prevent adhesion between the two materials. The outer steel tube encases the core and provides buckling restraint.

BRBs have the advantage of being low cost with an easy design and construction in comparison to other resilient technologies such as base isolation for example. Furthermore, they can be easily fitted into a structural frame and the structure does not

require a bespoke design. Since BRBs are in common use in buildings internationally and the technology is well-understood, there are comprehensive guidelines available for their design [35,36].

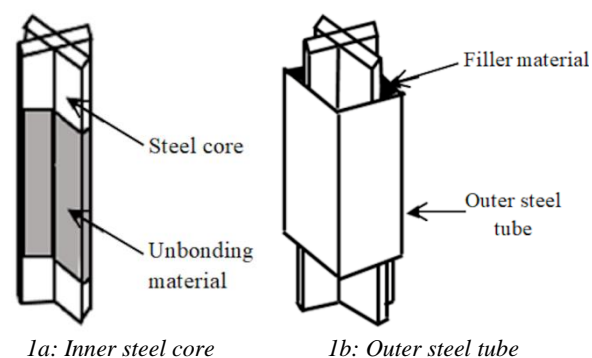


Figure 1: Cross-section of a buckling-restrained brace (modified from [9]).

BRBs are designed to yield under small inter-storey drifts [10] in order to dissipate energy in the building and concentrate plastic demand in the braces. However, when a large earthquake occurs and causes a significant inter-storey displacement, other structural members such as beams and columns may also be subjected to damage. In addition to this BRBs are vulnerable to ratcheting and large residual displacements. Hence, there is debate in the engineering community about whether BRBs can be classified as a low damage system. Furthermore, BRBs are typically characterised by high floor accelerations in comparison to other low damage technologies such as base isolation and viscous damped structures, which can damage a building's non-structural elements and building contents.

Among the buildings using this technology, the PwC Centre (see Table 1) uses BRBs around the whole periphery of its building, as photographed in Figure 2, to restrict lateral movement in multiple directions. The bracing systems on the west, east, north and south elevations of the building are shown in Figure 3.

Table 1: Building identification of PwC Centre.

Location:	60 Cashel Street, Christchurch Central City, Christchurch 8013 (-43.533052, 172.632403)
Sector:	Commercial
Client:	Bridgewater Properties Limited
Tenants:	PricewaterhouseCoopers, Chapman Tripp, Air New Zealand, Crombie Lockwood, Tonkin + Taylor
Architect:	Warren & Mahoney
Civil/Structural Engineer:	Beca Christchurch
Contractor:	Armitage Williams Construction
Length of design stage:	11 months
Length of construction stage:	22 months
Date of completion:	November 2016

A key aim in design was to use a lightweight system that would minimise construction costs. The designers therefore opted for a steel fabricated structure (see Table 2).



2a: Elevation 2b: Bracing system at base

Figure 2: PwC Centre.

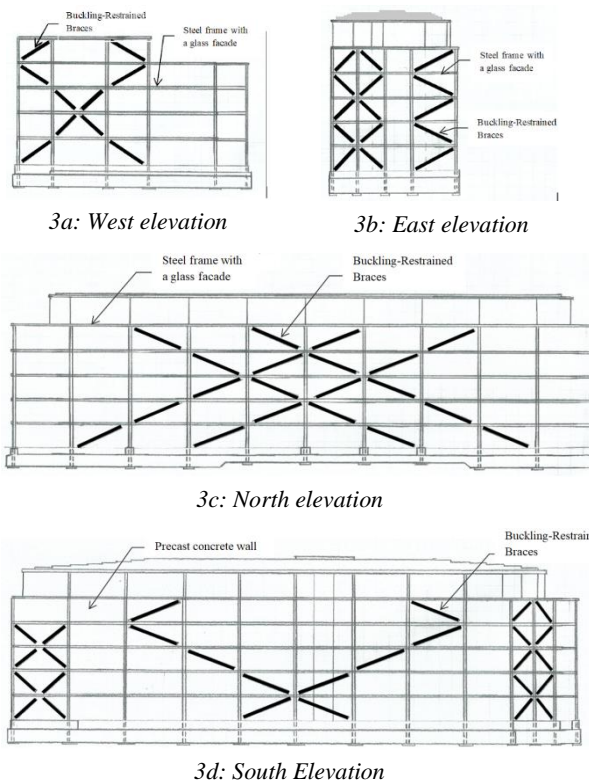


Figure 3: Elevation of PwC Centre (adapted from engineer’s drawings).

A glass facade covers three sides of the building, providing an aesthetic and architectural design. The glass was designed to be operational under a 0.45% drift. The bracing system of the building is located behind the glass façade, allowing free rein for architects in the façade design.

In low-magnitude earthquakes, the PwC Centre is expected to undergo negligible structural damage. However, in large-magnitude earthquakes, such as those of the 2010 and 2011 Canterbury earthquakes, a proportion of the BRBs are expected to yield and require replacement, which was estimated to take a period of 3-4 months. As the BRBs in the PwC Centre use pinned connections to connect to the frame of the building, they can be removed without disrupting the structural elements.

The main driver for using a resilient design in the PwC Centre was the tenant, PricewaterhouseCoopers. They requested that the building be built to an Importance Level 3 (see Table 3) so that their occupants and high value contents could be provided with more protection in the event of an earthquake [37].

Table 2: Building geometry and materials used in the PwC Centre.

Building geometry			
Elevation	Number of levels:	5 storeys	
	Elevation above ground-level (m):	21	
	Height of storeys (m):	Level 1:	4.1
		Levels 2-5:	3.85 per storey
Plan	Floor area (m ²)	Level 1:	2200
		Levels 2-4:	1800 per storey
		Level 5:	1600
Building materials			
Horizontal	Foundations	Reinforced concrete raft foundation	
	Floors	Composite floor comprising corrugated steel sheets with concrete infill	
Vertical	x- direction (East–West)	Steel frames comprising steel beams, and columns constructed of concrete infill with steel reinforcement, braced using BRBs, and with a glass facade	
	y-direction (North–South)	North: Steel frame, braced with BRBs and glass façade. South: Elevation includes both a BRB-braced steel frame for lateral resistance and a precast concrete wall for fire resistance	
Features of seismic-resilient technology used	Buckling-Restrained Braces along four sides of building perimeter to provide lateral resistance		

Table 3: Design limits of PwC Centre.

Importance level:	IL3
Maximum inter-storey drift:	1.9% ULS
Ultimate Limit State Event (ULS):	1 in 1000 year

The structural engineers, Beca, drove the decision to use BRBs in the PwC Centre for a number of reasons. Firstly, BRBs provided a relatively economical solution that easily accommodated the architectural design, and were easy to procure and install. Secondly, their design procedure is well documented and codified [36,38] which allowed for easier design and gave the engineers assurance that the technology was trusted and tested.

Rehua Building: Example of Viscous Dampers

When viscous dampers are used, the critical damping ratio in a building is increased from 2-5% to 20-30% [39], which greatly reduces the ground-motion induced drifts and accelerations, and hence damage [12].

A viscous damper (see Figure 4) comprises a stainless steel piston, a steel cylinder that is split into two chambers, and a compressible hydraulic fluid, often silicone oil [12]. During an earthquake, a structure’s movement is transmitted via the viscous damper to the damper fluid to dissipate the earthquake

energy. After an earthquake, the pistons in the viscous dampers return to their original position which, when paired with a re-centering system, removes the need for reconstruction or manual re-centering [39].

The principle behind using viscous dampers is to limit the drift and acceleration in the building or to limit the ductility demands on existing structural elements so that damage in other structural and non-structural elements can be avoided. Furthermore, no replacement of the dampers is expected to be required after a seismic event [14].

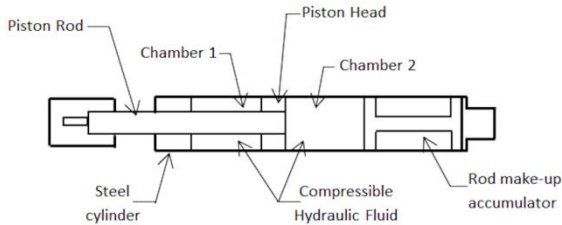


Figure 4: Fluid viscous damper (adapted from [12]).

The benefits of using viscous dampers over other technologies include their easy incorporation into a structure without modifying the design, and their easy application in the retrofit of existing structures. Viscous dampers respond out-of-phase with other yielding elements in the primary structure of a building and therefore if used in retrofit, peak foundation loads can be greatly reduced in comparison to using other technologies such as BRBs. As a result they may not require foundation strengthening [29].

Among the buildings using viscous dampers is the Rehua Building (see Table 4), located on University of Canterbury campus, which was a retrofit project of the former Commerce Building following damage suffered in the 2011 Canterbury earthquake [40]. Images of the Rehua Building's seismic-resisting system are shown in Figure 5.



5a: Building 5b: Internal viscous damper 5c: Internal viscous dampers

Figure 5: Rehua building.

Table 4: Building identification of Rehua building.

Location:	University of Canterbury, 20 Kirkwood Avenue, Upper Riccarton, Christchurch 8041 (-43.523035, 172.584467)
Sector:	Education
Client and Tenant:	University of Canterbury
Architect:	Athfield Architects
Civil/Structural Engineer:	Holmes Consulting LP
Length of construction stage:	18 months
Date of completion:	2019

The retrofit involved the installation of fluid viscous-damped steel frames and buckling-restrained braced frames inside the existing concrete moment frame. Details of the structural elements in the building and its design limits are given in Table 5 and Table 6.

Table 5: Building geometry and materials used in Rehua building.

Building geometry		
Elevation	Number of levels	North Block: 6 storeys South Block: 8 storeys
	Elevation above ground-level (m)	Approximately 27m
Plan	Floor area (m ²)	North Block: 700 per storey South Block: 400 per storey
	Building materials	
Horizontal	Foundations	Individual tied-in pad footings on a gravel layer
	Floors	200mm Precast Hollowcore units with 70mm mesh-reinforced concrete topping slab
	Roof	North Block: Light weight roof South Block: Concrete slab
Vertical	x- and y-direction	Two-way reinforced concrete moment frame
Features of seismic-resilient technology used	Viscous-dampened steel frames, with additional BRBs in ground to third floor	

Table 6: Design limits of Rehua building.

Importance level:	IL3	
Maximum storey drift:	North Block:	x-direction: 0.9% ULS z-direction: 1.0% ULS
	South Block:	x-direction: 1.4% ULS z-direction: 1.0% ULS
Ultimate Limit State Event (ULS):	1000-year return period	

Viscous dampers are used over the full height of the building to reduce drifts and accelerations. Since the additional 30% critical damping provided by the viscous damped system was not sufficient to limit the drift to acceptable values at the first storey [29], additional stiffness was provided by installing BRBs in the lower levels from ground to third floor.

The retrofitted building is not expected to exceed a 1.5% inter-storey drift at ULS [29]. While viscous dampers will not require repair after such an event, damage may occur in the reinforced concrete moment-frame beams and BRB elements. In this case, a period of repair and building closure would be required. Nevertheless, extensive damage and re-construction is not expected.

The client drove the decision to use a seismic-resilient design in the new Rehua building following the damage to the Commerce building in the 2011 Canterbury earthquake. Rather

than designing a new resilient building, the engineers proposed a retrofit of the original building using a structure that would fit within the existing frame. This provided a more economical alternative to re-constructing the building, thereby saving money, resources and time.

A key driver in the engineer's decision to use viscous dampers and BRBs was their flexibility in installation and design for a retrofit project, while still providing good structural performance. The combination of technologies allowed for an efficient means of reducing drift and floor accelerations in the building, which were the main causes of damage in the former Commerce building. An additional benefit was the compliancy of the design with the existing foundations. However, the architects and engineers had difficulty in designing and detailing the facade to accommodate large movements associated with the moving pistons, particularly at the corners of the building, and detailing connections of the new frame to the existing structure. Additionally, the contractors had difficulty in retrofitting the two frames, detailing connections, and constructing the facade to accommodate movement. This was aided by early coordination with the viscous damper supplier about the design of connections, fabrication and erection tolerances, and site installation methods leading to a successful installation of the units on-site [29].

Tūranga Library: Example of Concrete Rocking Walls and Steel Moment Resisting Frames

Rocking structures consist of frames or walls that accommodate seismic displacement through a rocking motion as shown in Figure 6, and avoid the formation of plastic hinges [16,41]. The main elements are connected together, and to the foundations, using post-tensioned tendons, which allow re-centering in the structure. Supplemental dissipation devices, such as shear fuses, are located at the rocking interface [17]. Rocking structures can be constructed of steel [11,17,18], concrete (also known as PRESS [21,22,42,43]) and timber (also known as Pres-Lam [44,45]).

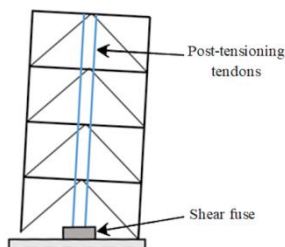


Figure 6: Self-centering steel rocking frame (adapted from [12]).

Such technology has the advantage of providing controlled rocking and re-centering to a building while minimising damage to the structure. The plastic demand is concentrated in replaceable fuses, thereby removing the need for replacement of other less easily removable components after a seismic event. However, in order to remain undamaged during an earthquake, the non-structural elements and floor slabs need to be designed to withstand the rocking motion [46]. The cost of rocking structures is comparable to BRBs and generally lower than that of base isolation. However, they do not offer the same architectural flexibility.

Among the buildings using rocking structures is the Tūranga Library (see Table 7), which was one of the anchor projects in the redevelopment of Christchurch following the 2011 Canterbury earthquake [30].

Table 7: Building identification of Tūranga library.

Location:	60 Cathedral Square, Christchurch Central City, Christchurch 8011 (-43.529811, 172.637182)
Sector:	Community
Client:	Christchurch City Council
Use:	Public library for community
Architect:	Architectus
Civil/Structural Engineer:	Lewis Bradford Consulting Engineers
Contractor:	Southbase Construction
Length of design stage:	12 months
Length of construction stage:	25 months
Date of completion:	October 2018

The building uses two low damage systems: concrete rocking walls around the central core areas, and steel moment resisting frames with rocking column base connections around the building perimeter (see Table 8). The concrete walls provide approximately 75% of the total seismic resistance in the building, and the steel frames provide 25% [30]. The shear walls contain unbonded post-tensioned steel tendons that run through the walls and connect them to the foundations, providing a self-centering system in the building. Damping is provided by easily replaceable U-shaped flexural plates located at the end of each wall, where movement is greatest, and high force to volume lead dampers (HF2V dampers) [30] located at the base of the walls. The HF2V dampers can undergo significant damping without experiencing damage.

Table 8: Building geometry and materials used in Tūranga library.

Building geometry		
Elevation	Number of levels	5 storeys
	Elevation above ground-level (m)	Approximately 17
Plan	Total floor area (m ²)	10,000
Building materials		
Horizontal	Foundations	Grillage of concrete foundation beams
	Floors	Prestressed precast ribs with timber infills and topping slab
	Roof	Steel portal frame encasing a roof level plant room
Vertical	x- and y-direction	Steel moment resisting frames around perimeter, with concrete-filled tubular composite columns and steel beams. Concrete hybrid rocking walls used in central cores.
Features of seismic-resilient technology used		Hybrid concrete shear walls and a steel moment resisting frame. UFPs and dampers used.

The steel moment resisting frames are stiff and provide high torsional resistance which reduces building movement [30].

Tūranga Library is designed to withstand up to a 1/1000 year earthquake with peak drifts of 1.5-1.6% [30], and return to its original position with minimal structural damage incurred. Any systems damaged in this event will be easily repairable. The U-shaped flexural plates and HF2V dampers are designed to take the large forces and damage induced during an earthquake so that damage to other elements can be reduced.

The client, Christchurch City Council, set stringent performance criteria for Tūranga with a required Damage Control Limit State (DCLS) for an earthquake of a 250-year return period, and requested it to be designed as an Importance Level 3 (IL3) building (see Table 9). Such criteria were set because the library was a prominent city building and at the forefront of the redevelopment of Christchurch, where a high performance building would demonstrate the city's commitment to protecting the community. To meet the high performance criteria, the engineers drove for a seismic-resistant design to be used.

Table 9: Design limits of Tūranga Library.

Importance level:	IL3
Allowable inter-storey drift:	1.8% ULS
Ultimate Limit State Event (ULS):	1000-year return period
Damage Control Limit State Event:	250-year return period

The engineers drove the decision to use a steel moment resisting frame and concrete rocking walls to meet the performance requirements and budget constraints, provide a self-centering component, and to not conflict with the architect's design. The use of a dual resisting system provided assurance to the client that sufficient protection would be provided.

Southern Cross Hospital: Example of Rocking Concrete Frames and Walls (PRESSSS)

Southern Cross Hospital (see Table 10) is a five-storey building which is classified with a high importance level given its necessity to be operational in the case of emergency post-earthquake.

Table 10: Building identification of Southern Cross Hospital.

Location:	131 Bealey Avenue, Richmond, Christchurch 8013 (-43.520038, 172.635096)
Sector:	Health
Client:	Southern Cross Health Trust
Use:	Community hospital
Architect:	Warren & Mahoney
Civil/Structural Engineer:	Quoin (Structex Metro at the time of construction)
Contractor:	Warren and Mahoney
Length of design stage:	10 months
Length of construction stage:	12 months
Date of completion:	August 2010

The PREcast Seismic Structural System (PRESSSS) in place uses a coupled rocking wall and frame system (see Figure 7). Concrete rocking walls run in the east-west direction, and concrete rocking frames run in the north-south direction. The unbonded walls are coupled using U-shaped flexural plates (UFPs) to provide shear transfer between the walls and increase the damping in the system (see Table 11).

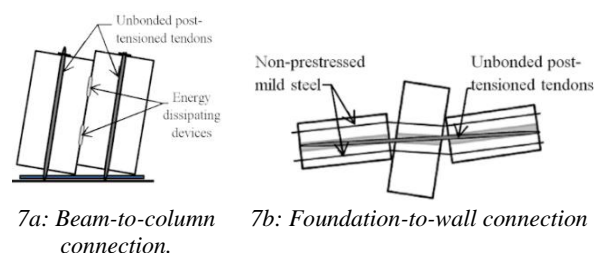


Figure 7: Rocking motion in a PRESSSS (modified from [12]).

Table 11: Building geometry and materials used in Southern Cross Hospital.

Building geometry		
Elevation	Number of levels	4 storeys and 1 basement
	Elevation above ground-level (m)	12.4
	Height of storeys (m)	2.8 – 4.2 per storey
Plan	Floor area (m ²)	Approximately 520-550 per storey
	Building materials	
Horizontal	Foundations	Reinforced concrete foundations on piles
	Floors	Pre-stressed concrete Hollowcore units with topping
	Roof	Long run roofing supported by steel purling and rafters
Vertical	x- direction (East-West)	Two full-height and three half-height post-tensioned concrete shear walls
	y-direction (North-South)	Four precast concrete post-tensioned frames
Features of seismic-resilient technology used		Unbonded post-tensioned tendons in precast members. Walls coupled by U-shaped flexural plates.

Southern Cross Hospital was constructed prior to the 2010 and 2011 Canterbury earthquakes. During these high-magnitude earthquakes, the building performed well in resisting lateral movements, and returned to its original position without significant damage to the building or its contents. The hospital was therefore able to remain operational. There was minor damage to non-structural elements of the building after the 2011 earthquake, which required a three month repair period, during which the hospital was able to remain open. It is expected that, following a similarly large, or lower, magnitude earthquake, Southern Cross Hospital will again suffer minor damage that

can be repaired without major disruption, and the hospital will be able to remain open for use.

The engineers at Quoin drove the decision to use a resilient design in Southern Cross Hospital. The hospital was designed in 2009, when there was less drive for seismic-resilient designs, especially when it may incur a cost or time penalty for the client. However, the engineers on the project understood the need for seismic-resilience in a high importance level building such as a hospital, and so encouraged the clients to use such a design. The design limits of the building are given in Table 12.

The engineers drove the choice for concrete rocking (PRESSS) technology to be used as it was considered to be the most cost-effective design, and was expected to sufficiently preserve a hospital and its valuable contents. It also allowed for easier construction than the base isolation option.

Table 12: Design limits of Southern Cross Hospital.

Importance level:	IL3	
Allowable inter-storey drift:	x-direction:	1.8% ULS
	y-direction:	2.0% ULS
Ultimate Limit State Event (ULS):	1 in 1000 year	

Beatrice Tinsley Building: Example of Rocking Timber Frames (Pres-Lam Technology)

The Beatrice Tinsley building (see Table 13), located in University of Canterbury campus, is a 4-storey building that was designed to be a science hub in the University [47]. The building is photographed in Figure 8.



8a: Building

8b: Braced LVL frames

Figure 8: Beatrice Tinsley building.

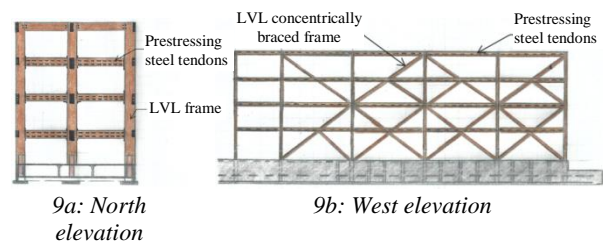
Table 13: Building identification of Beatrice Tinsley Building.

Location:	University of Canterbury, 20 Kirkwood Avenue, Upper Riccarton, Christchurch 8041 (-43.522556, 172.583101)
Sector:	Education
Client and Tenant:	University of Canterbury
Architect:	Jasmax
Civil/Structural Engineer:	Beca, in collaboration with PTL
Contractor:	Dominion Constructors Ltd.
Length of construction stage:	18 months
Date of completion:	October 2019

The building uses a combination of post-tensioned timber moment-resisting frames spanning in the East-West direction and timber concentric braced frames spanning in the North-South direction (see Table 14). Replaceable steel angles are located at the rocking interface of the post-tensioned timber moment-resisting frames to provide energy dissipation [48]. Elevations of the seismic resisting system are shown in Figure 9. The use of timber, as opposed to steel and concrete, has the benefits of providing a more aesthetic and sustainable design.

Table 14: Building geometry and materials used in Beatrice Tinsley Building.

Building geometry		
Elevation	Number of levels	4 storeys and 1 basement
	Elevation (m) above ground-level	17
	Height of storeys (m)	3.9 – 4.3 per storey
Plan	Floor area (m ²)	Levels 1 and 2: 1412 per storey Levels 3 and 4: 662 per storey
	Building materials	
Horizontal	Foundations	Reinforced concrete foundations from existing building, consisting of continuous shallow strip footings
	Floors	Potius floor panels: LVL joists fixed to a plywood layer
Vertical	x-direction (East-West)	Post-tensioned timber moment-resisting frames
	y-direction (North-South)	LVL columns, with LVL concentrically braced frames
Features of seismic-resilient technology used		Unbonded steel bars in timber members of moment-resisting frames. Steel angles act as dissipators.



9a: North elevation

9b: West elevation

Figure 9: Elevations of Beatrice Tinsley Building (adapted from drawings kindly provided by PTL).

It is predicted that the design in the Beatrice Tinsley building will be sufficiently resistant to protect the structure in low magnitude earthquakes due to its stiff frame and re-centering properties. However, as the building was designed to meet the required levels of performance as specified in the code, rather than low damage requirements, it is expected that in large magnitude earthquakes the Beatrice Tinsley Building will undergo sizeable displacements at roof level. After such an event, a period of repair will be required, or if severe, reconstruction will be needed. In addition, the steel tendons can yield in large magnitude earthquakes [12], and would require replacement as a result. The design limits of the Beatrice Tinsley building are given in Table 15.

Table 15: Design limits of Beatrice Tinsley Building.

Importance level:	IL2
Allowable inter-storey drift:	2.3% ULS
Ultimate Limit State Event (ULS):	1 in 500 year

The client, University of Canterbury, drove the decision to use Pres-Lam technology in the building. There were multiple reasons driving their choice. Firstly, timber is becoming increasingly popular in building design across the world [49], including in universities. As a university, the client recognised the commercial and environmental advantages of using it in their building. Secondly, the site had an existing underlying basement which had to remain operational during construction. The extensive foundations required for base isolation or a concrete building were therefore unsuitable. Thirdly, Pres-Lam technology was initially developed at University of Canterbury. The use of Pres-Lam in the Beatrice Tinsley Building therefore provided a valuable link between university research and the ongoing development of the University's infrastructure, which provided good marketability.

Justice and Emergency Service Precinct: Example of Base Isolation

Base isolation is one of the most popular seismic-resilient technologies in use [50] because of the high level of protection and structural performance it provides to a building.

The technology uses flexible connections called isolators [12] to decouple a building from its foundations. This minimises the transfer of horizontal earthquake forces between the ground and building, thereby reducing damaging vibrations occurring in the structure.

There are three common types of base isolation: lead rubber bearings, sliding systems and friction pendulums [12], all of which are located at the isolation plane. Lead rubber bearings consist of alternating laminated layers of thin rubber and steel plates, with a lead 'plug' in the centre which acts as a damping system. The rubber in the bearing provides flexibility in the connection and generates a self-centering property. The interspersed layers of steel are used to provide vertical rigidity and stiffening to the isolator [12]. Sliding systems are used as a low friction system to limit the transfer of shear across an isolation plane. The building can slide freely on the bearing. Friction pendulums comprise a concave sliding surface and an articulated friction slider, all contained in a cylinder to restrict lateral displacements [12]. The pendulums allow the isolated structure to rock during an earthquake while dampening the earthquakes forces transferred with their frictional interface [51].

As a base-isolated superstructure will undergo less motion during an earthquake than a non-isolated building, the structural and non-structural elements are expected to undergo little damage, and the building is expected to remain operational after large-magnitude earthquakes [12]. Due to its high level of protection, base isolation is commonly used in importance level 3 and 4 buildings [52], where the structure and its contents must be preserved and the building is required to remain operational.

Base isolation has the advantages of mitigating both inter-storey drift and high floor accelerations [25] (a unique feature in resilient design). The main design challenge arises from the need to ensure building services have sufficient displacement capacity at the isolation plane [26].

Among the structures using base isolation are the Justice and Emergency Services Precinct (Table 16), which was developed

as part of the re-build of Christchurch's central city following the 2011 Canterbury earthquake [33]. The precinct contains four buildings housing the Justice Sector and Law Departments in three of the buildings, and the Police and Emergency services in the fourth. The Precinct is photographed in Figure 10.

Table 16: Building identification of Justice and Emergency Services Precinct.

Location:	20 Lichfield Street, Christchurch Central City, Christchurch 8011 (-43.534451, 172.634187)
Sector:	Governmental
Client:	Ministry of Justice
Tenant:	Departments of Justice, Police, Law and Emergency Services
Architect:	Warren & Mahoney, in collaboration with Cox and Opus Architecture.
Civil/Structural Engineer:	Holmes Consulting LP
Contractor:	Fletcher Construction
Length of design stage:	12 months
Length of construction stage:	18 months
Date of completion:	September 2017

**Figure 10: Justice and Emergency Services Precinct**

The four seismically separated buildings surround a central courtyard and are isolated on one common podium; all the buildings therefore receive the same isolation effects. The isolation plane is located under first floor level. 82 flat-plate pot-bearing PTFE sliders and 50 Lead-Rubber Bearings are supported on cantilever ground floor reinforced concrete columns [33]. The structural elements used in the Precinct are given in Table 17. A first floor plane was chosen as it removed the need for a basement and significant foundation excavation, thereby saving time and money in construction. However, isolating at first floor requires that the ground floor structural and non-structural elements be designed for fixed-base accelerations, and the movement of the isolation plane must be accommodated in the non-structural details.

All four buildings in the Precinct were designed to limit SLS2 building storey drifts to a maximum of 0.5%, which resulted in maximum ULS building storey drifts of 0.9% [33]. The three Justice Buildings were designed to meet IL3 standards, whereas the Emergency Services Building was designated a higher importance level of IL4 and was therefore designed to experience smaller drifts than the Justice buildings (Table 18). As a result of its high importance level, the Emergency Services Building is expected to remain operational after large earthquakes. The Justice Buildings will undergo larger drifts

but as they are located on the same isolation plane as the Emergency Services building, they receive the same isolation effects and as a result it is expected that certain rooms in the Justice buildings will be able to remain operational.

Table 17: Building geometry and materials used in Justice and Emergency Services Precinct.

Building geometry		
Elevation	Number of levels	5 storeys
	Elevation above ground-level (m)	25
	Height of storeys (m)	4 – 4.3 per storey
Plan	Gross floor area (m ²)	40,000
Building materials		
Horizontal	Foundations	Reinforced concrete raft slab. Ex-situ soil-cement mixing using in ground to mitigate potential liquefaction.
	Floors	ComFlor 80 composite metal deck with topping slab, supported on cellular secondary beams
Vertical	Below level 1 (isolation plane):	Isolators supported on circular cantilever cast insitu reinforced concrete columns
	Above level 1 (isolation plane):	Two-way structural steel moment resisting frames with columns made of concrete filled tubes (CFT)
Features of seismic-resilient technology used		Isolation plane located below level 1. 82 flat-plate pot-bearing PTFE sliders and 50 Lead-Rubber Bearings under columns in primary structure.

Table 18: Design limits of Justice and Emergency Services Precinct.

Importance level:	Emergency Services Building:	IL4
	Law and Justice Buildings:	IL3
Maximum inter-storey drift:	Emergency Services Building:	0.6% ULS
	Tuam Building (Justice):	0.7% ULS
	Lichfield Building (Justice):	0.6% ULS
	Durham Building (Justice):	0.9% ULS
Ultimate Limit State Event (ULS):	2500-year return period	

Due to the function of the buildings as centres for emergency services, and the corresponding code requirements, the Police and Emergency Services were classified as an Importance Level 4 facility to ensure that the building would remain operational, or would be able to return to a fully operational state within an acceptable short timeframe, after an SLS2 earthquake with a

500 year return period [53], and would therefore be able to provide essential post-earthquake services. Using a resilient design had the additional benefit of reassuring the tenants that the building was safer to occupy during a large-magnitude earthquake than a non-resilient building.

The client drove for the use of base isolation as it was considered the safest and most effective seismic-resilient design. At the time of building conception, most IL4 structures in New Zealand used base isolation. Base isolation had the additional benefit of removing the need for structural walls and braced frames in the building above. Braced frames were an undesirable feature architecturally as they affected the future flexibility and circulation of the building. It was the engineers' suggestion that all of the four buildings be placed on the same isolation plane so the buildings did not have to be designed with separate resilient systems. Using one common podium had the additional benefit of significantly reducing the differential horizontal movement that the link bridges connecting all four buildings had to be detailed for, thereby reducing cost and difficulty in design.

KEY FACTORS DRIVING FOR LOW DAMAGE VS TRADITIONAL DESIGN

Main Stakeholders in Low Damage Design

For the six projects studied, the percentage of influence that a stakeholder had in driving for the use of a low damage design in their project is presented in Figure 11. The results present the perspective of the design engineers, obtained during interview, on how much each stakeholder influenced this decision. For instance, whether the client originally commissioned for a resilient design (100% client influence) or there was discussion about resilience between the engineers and clients during design (50% client influence and 50% engineer influence). It can be seen that, among the five stakeholders identified in the design process, the main drivers for a low damage design were the building users (either they were owners/clients or tenants) or the structural engineers.



Figure 11: Driver in choosing a low damage design.

The percentage of projects driven by each stakeholder is given as a pie chart in Figure 12. It can be seen that clients and tenants make up 58% of the drivers, while structural engineers represent 42%. The reasons for their choices are reported in Table 19, and they range from wanting the building to remain operational after a large earthquake event, to wanting to promote the use of low damage technologies.

As seen in Figure 12, the number of seismic-resilient projects driven by clients was equal to that driven by engineers. The proportion of clients driving for a low damage design was dependent on their awareness of the importance of seismic-resilience. Those who had previous experience of large-magnitude earthquakes, such as the 2010 and 2011 Christchurch earthquakes, were keen for a resilient design. However in projects with less knowledgeable clients, such as

those who did not reside in Christchurch for the 2010 and 2011 earthquakes, the engineers had to drive for a low damage design to be used to protect high-importance buildings, and educate the clients on the benefits and importance of resilient structures. The client’s final decision on whether to use a low damage design was often dependent on associated cost, and a significant influence in the choice of design was the consequent publicity for both clients and engineers (Table 19).

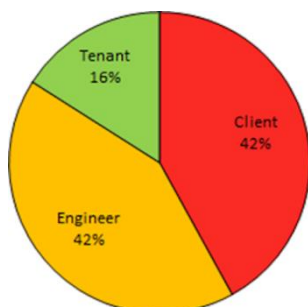


Figure 12: Proportion of low damage designs driven by each group.

Table 19: Reasons driving the choice of a low damage design.

Driver	Reason for choosing a seismic-resilient design
Client	<ul style="list-style-type: none"> Client’s building had suffered damage in previous earthquakes Wanted building to remain operational post-earthquake Wanted to lead the recovery of the city following the Canterbury earthquakes Publicity – to promote the use of seismic-resilient technology in the city
	<ul style="list-style-type: none"> Wanted to preserve high importance buildings in an earthquake event Publicity – using a seismic-resilient design in a community building at the forefront of the city’s redevelopments shows the city, and engineer, in a good light
	<ul style="list-style-type: none"> Wanted a safe building to occupy as they had been affected by previous earthquakes

In a small proportion of projects, the tenants drove for a low damage design. In these cases, the tenants had experienced previous earthquakes and wanted assurance that they would now be occupying a safe building. They were aware that better protection would be provided by a resilient structure.

Drivers in Choice of Seismic-Resistant Technology

Engineers were asked to evaluate the most important factors that influenced their choice of low damage technology to use. Within this framework, five main factors were found to impact their selection: structural performance; cost; ease of construction; associated publicity; and the availability of design guidelines. The percentage of projects studied that were influenced by each factor are shown in Figure 13.

The most dominant factors driving the choice of low damage technology were structural performance and cost. When the leading objective in design was to provide a high level of protection to the building, the choice of low damage technology was based on the most appropriate and effective design for the level of protection required, rather than cost. For the high-

performance buildings studied, a self-centering property was desirable, and a reliable and well tried-and tested method were often sought after. In projects where a high level of structural performance was less important, the main driving factors were publicity, ease of construction and cost. For architecturally significant buildings, a system that could easily fit around their design, and allowed for free elevations and internal space were required.

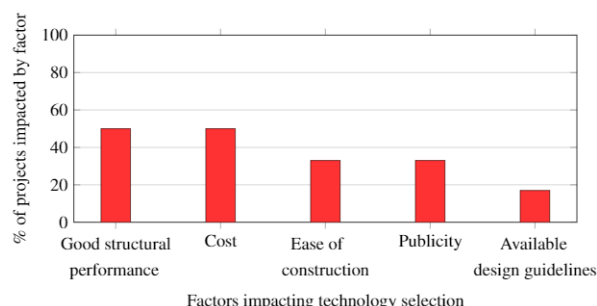


Figure 13: Factors driving selection of technology.

Client’s Familiarity with Low Damage Design

To investigate the possible correlation between client familiarity with low damage technologies and their usage, structural engineers were asked to rank their clients’ familiarity with low damage design. Three possible answers were identified:

- Not very familiar, where clients had never or barely heard of low damage design;
- Familiar, where clients were aware of resilient buildings but were unaware of its benefits and costs;
- Very familiar and advocates for low damage design.

It was found that in 83% of projects, the clients were familiar or very familiar with low damage design, as shown in Figure 14. It should however be noted that this sample is bias as it only represents clients who chose to use a low damage design in their building. In 33% of the cases studied, the client specifically commissioned for a particular low damage design. It is interesting to see that in the remaining 67%, the clients originally commissioned for a traditional design before being made aware of the benefits of resilience by the engineers, including the enhanced performance, safety and longevity of the structure, which highlights the significance that structural engineers had in influencing their choice and the importance of the structural engineers’ role in the decision process.

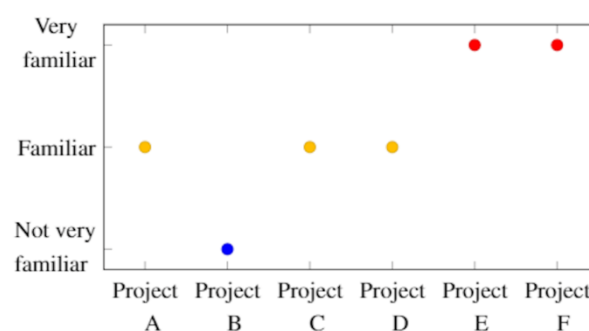


Figure 14: Familiarity of client with low damage design in each project.

The relationships between client familiarity with low damage design and the client’s industry of work are presented in Figure 15. Four industries of work were identified for the projects studied:

- Public sector, including local councils and governmental associations (two projects);
- Research sector, which focused on universities and academic institutions (two projects);
- Health, particularly hospital and health organisations (one project);
- Business, such as those companies involved in the finance industry (one project).



Figure 15: Knowledgeability of clients in different industries about low damage design.

As seen in Figure 15, the 33% of clients who were very familiar with low damage design, and commissioned for a particular resilient design, were in the public and research sector of work. These sectors are more exposed to the effects of earthquake damage and as a result understand better the benefits of low damage buildings. For instance, those clients working in the public sector in Christchurch, such as local councils, had experienced and managed the consequences of the extensive damage from the Canterbury earthquakes, and were therefore keen to future-proof the city from similar damage. Clients from other sectors were less aware of the benefits of low damage design, and required education by engineers before choosing a resilient system because their work was not directly impacted by earthquake damage. However, there was a fair client familiarity across all sectors, which highlights that there is an interest and awareness of low damage design across the general population of Christchurch. There is likely an overall fair client familiarity due in part to some clients suffering effects from recent earthquakes that were extremely disruptive to their businesses.

Additional Benefits to Clients from using a Low Damage Design

The benefits that clients received from using a low damage design, other than enhanced protection to their building, were recorded. The results shown are the design engineers' perspective, obtained during interview, of the additional influences that drove the client to use a resilient design. The results are presented in Figure 16, where the percentages of clients, out of the six projects studied, who received each additional benefit are shown.

In 43% of projects, clients chose to use a low damage design just for the protection it provided to their structure and occupants, which demonstrates that once educated about resilience by engineers, clients understood the need to protect their building. However, 57% of clients received additional benefits which were incentives in their decision to use a resilient design.

In 28% of cases, the building was designed for the use of a particular tenant who had requested a resistant building. When tenants wanted a resilient design, it was because they had previous experience of large magnitude earthquakes, and wanted reassurance that their new building would be safe to

occupy. In these cases, a low damage design was chosen to appease the tenants and secure their occupancy.

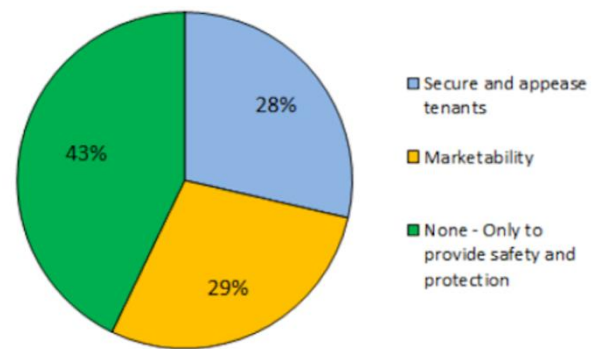


Figure 16: Additional benefits clients received from using a low damage design, as a percentage of the total number of six clients studied.

As seen in Figure 16, 29% of clients profited from the marketability associated with using an earthquake-resistant building. Marketability related to the use of innovative new technologies developed in Christchurch, and the use of seismic-resistance in prominent buildings in the city.

CHALLENGES EXPERIENCED BY DESIGNERS

For the projects studied, the engineers were asked to identify the main challenges they faced in design. Most of the engineers interviewed found the design detailing, and detailing of connections, the most difficult aspect in design. These difficulties arose because transferring a technology from the laboratory into a real application presents several challenges. When testing a new technology in the laboratory, features such as ease of design and construction are sometimes overlooked.

In studying the level of difficulty experienced by architects and contractors in accepting, designing and constructing low damage buildings, it was generally found that the most difficult aspect for both groups was designing and constructing non-structural elements, facades and connections to accommodate large movements.

In examining the construction process, it was found that all of the technologies studied caused difficulty for the contractors, and it was generally considered that many of the structures and resilient systems studied had a low buildability.

To minimise the setbacks caused by construction issues in building low damage structures, the development of new technologies should consider not only the design, but also the methods of assembly, with a focus on improving the buildability.

LIMITATIONS

There were limitations to the methodology used in the study which will have an impact on the results. Firstly, the study uses one building representative of each seismic-resistant technology, therefore the sample size is limited and excludes a comparison of results between buildings using the same technology. In addition, the population of engineers interviewed was a small proportion of all engineers involved in seismic-resistant design in Christchurch, and is therefore a small sample size to represent all the Christchurch buildings using each technology. Thirdly some of the results can be project-specific, such as the reasons driving the decision to use a low damage design, which may result in different responses being obtained when generalising for the whole category of buildings using each technology.

CONCLUSIONS

With Christchurch undergoing significant construction with low damage buildings, the city provides a great selection of resilient systems, subject to the same environmental conditions, to study their application and performance. The study assessed six different low damage technologies applied to buildings in Christchurch, focusing on their design, construction and performance. Results were obtained from interviews conducted with structural engineers involved in the projects to assess the systems from the perspective of those involved in the design and construction process. Focusing questions on three subjects: the specific application of the system; the comparison between the low damage system and a traditional design; and an overall comparison between the technologies, provided a wide perspective of the benefits and issues of each technology to each of the stakeholders, and a view of the value of low damage buildings to the public and clients. From this, the areas that need to be addressed in low damage design, both of existing technologies, and in the development of new technologies, in order to increase the efficiency of design and encourage clients to choose a resilient building, were identified.

In the study of the key factors influencing the choice between a low damage and a traditional design, it was found that one of the main incentives for clients choosing to use a low damage design was for the protection it provides to a building. However, in 57% of cases there were additional incentives that influenced their decisions, namely cost and publicity. The proportion of clients driving for a low damage design was equal to that of engineers, and was dependent on the clients' familiarity with resilience. There was a large client familiarity with low damage design (83%) in Christchurch, which is representative of the awareness among the general public, however 67% of clients still originally commissioned for a traditional design. Furthermore, the study found that only half of the engineers had existing knowledge in the design of the technologies. The assessment of engineers' aids in design revealed that the most common methods used were appointing external guidance, and the use of published design standards.

Through the comparison of the low damage technologies studied, it was found that the main factors driving the client's choice of system were its structural performance and cost. The most difficult aspect for engineers in design was design and connection detailing, and architects and contractors found the most difficulty in designing non-structural elements to accommodate large movements. In addition the systems studied were generally considered to be of low buildability by the contractors. However, despite all contractors experiencing difficulty in constructing low damage buildings, the ease of construction was considered in the technology choice of only two of six projects.

LOOKING AHEAD

The results of the study suggest that, once educated in low damage design, clients understood the benefits of and need for resilience and were keen to use it, and the engineers were essential in driving for resilience and educating clients. As clients were often swayed by the additional benefits that come from using a low damage design, these should be presented to clients during the design selection process and made widely available, to further expand the commission for resilient buildings. For instance, the long-term economic benefits, insurance benefits, marketability, and attraction of valuable tenants are all factors identified in the study that will attract clients to choose a low damage design over a traditional design. Developers of a new technology should also consider these incentives in their design as it would result in more low damage buildings being commissioned for, particularly in that technology. For example, minimising cost and providing

publicity cues, such as the use of sustainable materials like timber, would encourage clients to undertake a resilient design. Although there is wide client, and public, awareness of resilience in Christchurch, more focus is needed on educating the public on the benefits of low damage design and variety of systems available, to increase the demand for resilient buildings. With more public demand for low damage buildings, more clients, particularly clients like the local council, will commission for resistant designs to appease the community and attract valuable tenants.

Through the comparisons conducted between the technologies, it can be concluded that researchers developing a new technology should focus not only on creating a functioning design, but also on the practical use of the technology. This includes the durability, constructability, maintenance and cost of the technology when used in a building. As the cost and performance of a system have a great influence on the clients' decision to use a low damage technology, the optimisation of these factors should be a priority in design. However, as the ease of design and construction, in addition to the buildability of a system, have a great impact on the progress and time frame of a project, these should be an additional focus in the development stage. To improve the efficiency of the design stage, researchers developing a new technology should focus on producing design and construction aids for architects, engineers and contractors in each technology, in addition to developing guidance for those high performance technologies currently without standards. This will lead to an easier and less time consuming design and construction process. Any unfamiliarity and lack of in-house knowledge will therefore not discourage engineers or contractors from undertaking a new resilient design.

The guidelines that can currently be used in the design of timber rocking systems, BRBs, base isolation and viscous dampers are provided by the Structural Timber Innovation Company [54], American Institute of Steel Construction [55], NZSEE seismic isolation guidance [56], and Report MCEER-00-0010 from State University of New York [57], respectively. Guidance for the design of steel rocking frames and concrete rocking frames have been produced by Steel Construction New Zealand [58] and New Zealand Concrete Society [59] respectively.

ACKNOWLEDGEMENTS

We gratefully acknowledge the interviewed persons at Beca, WSP, PTL, Quoin, Holmes Consulting, and Lewis Bradford Consulting Engineers for their time. We gratefully acknowledge also the inputs from the reviewers.

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