

# Seismically Resilient Building Technology: Examples of resilient buildings constructed in New Zealand since 2013

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**ABSTRACT:** Traditional seismic design in buildings follows the long accepted principles of capacity design targeted at life safety, as well as avoidance of dangerous building collapse. Capacity design accepts damage to the primary structure, and takes advantage of this with the primary structure absorbing seismic energy to withstand earthquake attack. Whilst this is a safe and robust design method continuing to be used around New Zealand and the world, other structural design techniques are available which provide the opportunity to protect primary structural elements from irreparable damage following a seismic event. Their ability to respond to large seismic events without causing irreparable damage to primary structural elements, while maintaining life safety and preventing dangerous building collapse, is clearly advantageous.

Following recent earthquake events in New Zealand and the subsequent increased awareness of seismic risk, there has been significant interest in seismically resilient building technology. Since 2011, a significant number of new buildings have been constructed in New Zealand illustrating the different forms of seismically resilient building technology available.

This paper presents case studies of several different resilient design technologies, applied in New Zealand post 2013. These technologies include the use of friction pendulum base isolation, rocking K brace frames with hold-down springs, structural steel two-way moment frames using sliding hinge joints, heritage strengthening using post tensioned rocking buttresses and post tensioned rocking walls.

## 1 INTRODUCTION

### 1.1 Traditional Seismic Design

When a building is shaken by a large earthquake, the building's immediate response is to deflect sideways, thereby displacing its own self-weight. This displacement sets in motion large inertia forces which the building's primary bracing structure is designed to resist. Large buildings generate very large inertia forces and these forces are often much greater than the structural strength for which the building is designed for. To overcome this, a traditional method of ductile design is used. This ductile design allows the building structure to yield to the earthquake forces and dissipate the seismic energy. Energy dissipation is achieved by utilising the primary structure in a series of controlled failures, thereby absorbing the earthquake induced inertia forces and maintaining building stability (and therefore life safety). Whilst this is a robust and safe design method, experience has shown that traditional ductile buildings are highly susceptible to irreparable damage following a large earthquake, often resulting in building demolition.

### 1.2 Base Isolation

There has been significant interest in the application of base isolation to offset seismic stress, and this is a well understood technology which typically uses lead rubber bearings or concaved friction bearings with displacement capacities up to 700mm. The design allows a much reduced transfer of seismic force into the primary structure when compared to a traditional ductile design. While New Zealand designers have traditionally used lead rubber bearings as a base isolation device, Christchurch has seen New Zealand's first introduction of concaved friction slider bearings. Concaved friction slider base isolation devices are commonly referred to as friction pendulum bearings and characteristically transmit lower seismic forces into the structure and fit-out of buildings when compared to lead rubber bearings. This is

due to a lower inertia force being required from the building before the bearings start sliding, although the displacements are proportionally larger. Base isolation is currently the best method for dealing with high forces from earthquake induced horizontal ground shaking by providing separation between the structure and the ground, simultaneously dissipating seismic energy. The perceived expense associated with base isolation however, often limits their use to high importance and high budget buildings. However in most cases, base isolation of structures encompass only a small percentage of the total build cost (5% - 7%). This increase in construction cost needs to be considered in the context of significantly improved potential business continuity following a large seismic event and the aftershock sequence that follows. The resilient building designs discussed in this paper do not offer the same level of protection. However, they come at a lower construction cost. .

Christchurch Art Gallery Base Isolation Retrofit



EPS - Triple Friction Pendulum Bearing -2014

Transpower Pole 3 Converter Building



DIS – Lead Rubber Bearing - 2011

### 1.3 History of Resilient Building Design in New Zealand

Over the past ten or so years, New Zealand has continued to develop several different types of resilient building designs that showcase a variety of resilient design technologies and methods. Resilient building design was initially introduced into New Zealand in 2007. At this time the award winning Te Puni student accommodation building in Wellington [1] was designed using rocking concentrically braced frames with ringfedder hold down springs. [4]



**Te Puni Student Accommodation -2007** [1] using concentric braced rocking frames and ringfedder hold down springs [2]

In 2009 the award winning Nelson and Marlborough Institute of Technology (NMIT) came into fruition as an all timber multi-level post tensioned rocking wall structure combined with U shaped flexural

plates. [3] A small number of other resilient building designs have been introduced in New Zealand prior to 2011.



**Nelson Marlborough Institute of Technology – 2009** using post tensioned rocking timber shear walls

#### 1.4 Principles of Non Base Isolated Resilient Design

Resilient building design is often referred to as Low Damage Design or Damage Avoidance Design. It takes many different forms and in all cases it enables buildings to respond to significant seismic events, without causing irreparable damage to primary structural elements while maintaining a focus on life safety and avoiding dangerous building collapse. The fundamental principal behind the structural design of resilient buildings is ensuring seismic energy is dissipated and strain is concentrated into ductile replaceable parts, thereby protecting the primary structure from damage.

Ideally the best performing resilient designs incorporate systems that allow re-centring after a large earthquake. This is achieved by simply providing a restoring force. In a wall braced building it is easily achieved by post tensioning a wall vertically on its centreline and allowing the wall to rock back a forth in an earthquake. The post tensioning acts elastically through elongation and contraction, restoring the wall back to a vertical position. Energy dissipation is included in the overall system with replaceable ductile energy dissipaters that yield in tension and compression at the point of rocking, usually at the base of a wall. These act just like the shock absorbers in a car. The ductile energy dissipaters is often termed a ‘plug and play’ device, meaning it is replaceable after it has yielded. Following a large earthquake the intention is for the ductile energy dissipaters to be easily removed and replaced. This rapid retrofit process allows the integrity of the primary structure to be reinstated quickly. Resilient systems are designed to protect the primary structure from irreparable damage which allows the building to be quickly repaired and put back into normal life again.

Resilient Building Design accepts a greater level of seismic damage than base isolation, but with a reduced cost of the application. It is not possible to design and build structures which are totally damage-resistant under all earthquakes, so the term “resilient building design” should be used carefully. Resilient building design simply means that there should be less damage than in conventional construction during design level earthquake shaking. A resilient building should be occupy-able immediately after experiencing large shaking (design level) and might be occupy-able in a short time-frame after very large shaking. The cost premium for resilient building design applied to a regular building is typically between 1% and 3% of the total construction cost.

Resilient building designs in New Zealand to date have generally been bespoke and required an innovative application to be incorporated into the architectural fabric of a building. They are alternative solutions not found in regular design codes. The design philosophy is supported by research and development in concrete, steel and timber, and in New Zealand has been further developed by the University of Canterbury and the University of Auckland. Research and testing is now sufficiently advanced to allow structural engineers to access the design principals for resilient buildings. Different technologies feature different materials, and some resilient designs will re-centre a building after an earthquake and some will not. Performance certainly differs with design. The same is true for the cost

of implementation.

### **1.5 What is the benefit of resilient building design**

Until recently the only protection building owners had from the risk of earthquake damage was an insurance policy, and / or a high performing base isolated building. Code compliant buildings are far from indestructible, in fact it is more than feasible for a building to be damaged beyond repair. Consequently, designers need to make structures “tough” to withstand overstressing without collapse.

Resilient building design has the following benefits:

- More affordable than base isolation
- Facility can function post disaster (business continuity, economic recovery)
- Limited structural damage and repair to defined areas
- Life safety
- Lower insurance risk
- Suitability for both infrastructure and multi-level buildings
- Access to records immediately after a disaster
- Staff confidence in the building’s resilience
- Improved morale post-earthquake

### **1.6 Resilient Building Types**

Architectural and drivers of building function will determine the type of resilient building designed. Resilient buildings have the same primary structure as any conventionally designed building, i.e. shear walls, frames or braced frames. The key difference is the resilient components are integrated into the conventional structural form, usually as an accessible replaceable component with sufficient ductility to dissipate seismic energy. In general any structural form is capable of resilient detailing so architectural and building functionality drivers are not compromised.

The key resilient design features that have been implemented in new buildings since 2013 include the following:

- Concave friction slider base Isolation
- Pre-stressed ring-feder hold down springs
- Compression and tension yielding buckling restrained braces
- Compression and tension yielding energy dissipaters
- Replaceable frame shear links
- Sliding friction joints

Each approach has an associated cost premium linked to relative performance.

### **1.7 Resilient Buildings Components**

Resilient building design requires specifically designed replaceable building components to isolate yielding damage in a structure. The purpose of the components is to be sacrificial and provided a capacity limited fuse that is easily replaceable thereby protecting the primary structure. They are often referred to as ‘plug and play’ components. The following examples are components included within a resilient building design that allow buildings to perform in a resilient manor during large earthquake shaking.

Pre-stressed Ringfedder hold down springs [2]



Compression and tension yielding buckling restrained braces



Compression and tension yielding energy dissipaters



Replaceable frame shear links [8]



Sliding friction joints [5]



Fiction pendulum base isolation bearings



Lead Rubber base isolation bearings



## 1.8 New Zealand Resilient Building Design Case Studies

The 2011 Canterbury earthquake sequence has had a significant influence on the construction of resilient building designs in New Zealand. New building developments have demonstrated many different forms of resilient building design. Since 2013 resilient buildings have been primarily constructed in Wellington, Nelson and Christchurch, recognising the interest in geographical seismic risk and large population centres at these locations. In Christchurch alone there have been in excess of 26 new resilient building designs constructed following the Canterbury earthquakes since 2013, this includes approximately 10 base isolated buildings.

The following case studies are a selection of different resilient design technologies that have been implemented in New Zealand since 2013.

## Case Study 1 - The Terrace Stage 1 – Christchurch

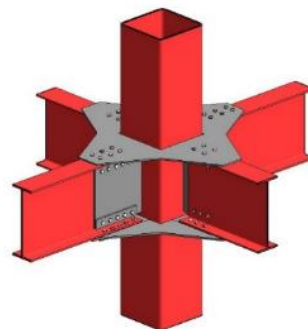
**Description** - Mixed use office and hospitality. The primary structural form is made of two way moment resisting frames to resist lateral loads.



**Resilient Technology** – The structural steel two-way moment frames have sliding hinge joints [5] to connect the beams to the columns in each direction

**How it works** – The moment capacity limited beam to column joint allows friction slippage of the bottom flange to occur whilst rotation about the top flange occurs during frame sway. The capacity limited beam to column joint protects the beam forming a plastic hinge during earthquake attack.

**Possible Repair** – Replacement of bolts in slipped joints and re-tensioning. The frame is expected to be 90% re-centring.

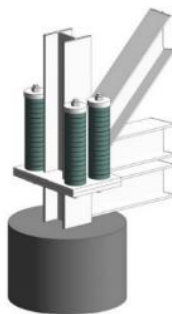
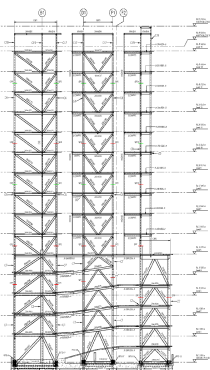


The Terrace Stage 1 - Two way sliding hinge joint frames

1.9

## 1.10 Case Study 2 – Elevate Apartments – Wellington [6]

**Description** – 15 Storey residential apartment building



Elevate Apartments - Rocking concentric brace frames with ringfedder hold down springs

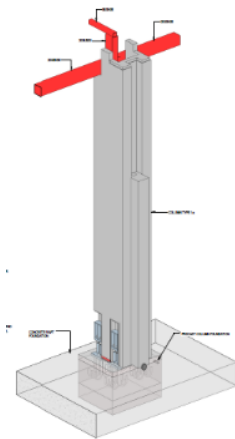
**Resilient Technology** - Structural steel concentric rocking braced frames using ringfedder hold down springs. [2] This building also incorporates one way structural steel moment frames using sliding hinge joints

**How it works** – The concentric braced frames are designed to rock and uplift at the base. Uplift is controlled by high compression ringfedder springs which dissipate energy during uplift and restore the frame to vertical. One way sliding hinge joints are used in the orthogonal direction to protect the beams from plastic hinge formation.

**Possible Repair** – Replacement of spring compression hold down bolts, and replacement of bolts in slipped joints and re-tensioning. The braced frames fully re-centre and the sliding hinge joint frames are expected to be 90% re-centring.

### 1.11 Case Study 3 – Knox Church– Christchurch

**Description** – Heritage church post-earthquake strengthening and repair using resilient design



Knox Church Rocking Buttress Structure

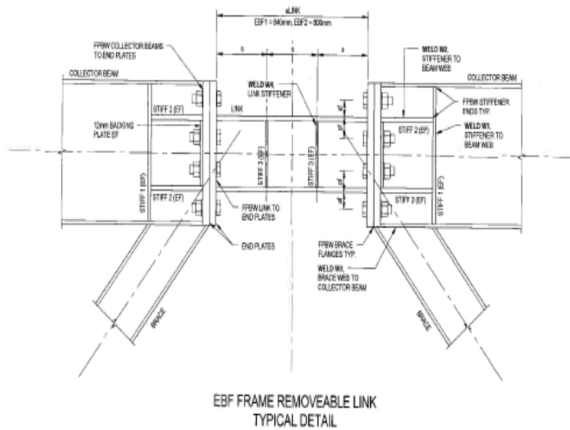
**Resilient Technology** – Post tensioned rocking buttresses [3] with plug and play energy dissipaters at the base of the rocking buttresses

**How it works** – Precast concrete buttresses are post tensioned to the foundations and are designed to cantilever in two directions from a raft foundation. The buttresses are designed to rock and uplift at the base. Energy dissipaters are located at the base of the buttresses which yield in tension and compression to dissipate seismic energy. The columns re-centre due to the column post tensioning.

**Possible Repair** – Replacement of the plug and play energy dissipaters

### 1.12 Case Study 4– Westpac Building – Christchurch

**Description** – 6 Storey commercial office building



Westpac Building with K Brace Replacable Shear Link

**Resilient Technology** - Structural Steel ductile K Braced frames using replaceable links in each direction. [7]

**How it works** – The ductile K Braced frames are designed for limited ductility and yield in shear. Following a large earthquake resulting in damage to the links, ductile links are detailed to be unbolted, removed and replaced.

**Possible Repair** – Replacement of the ductile links following seismic damage. New links will be fabricated to match any post-earthquake offset displacement at the link location. The building will remain in the post-earthquake deformed shape.

### 1.13 Case Study 5– 151 Cambridge Tce – Christchurch

**Description** – 6 Storey commercial office building



151 Cambridge Tce with triple friction pendulum bearing

**Resilient Technology** – Base isolated using Earthquake Protection Systems (EPS) triple friction pendulum bearing. First use of EPS triple pendulum bearings in New Zealand.

**How it works** – Moment resisting steel frames in each direction protected by triple friction pendulum bearing base isolation manufactured by Earthquake Protection Systems (EPS) in the USA. Overall size 914mm x 323mm with displacement capacity 570mm

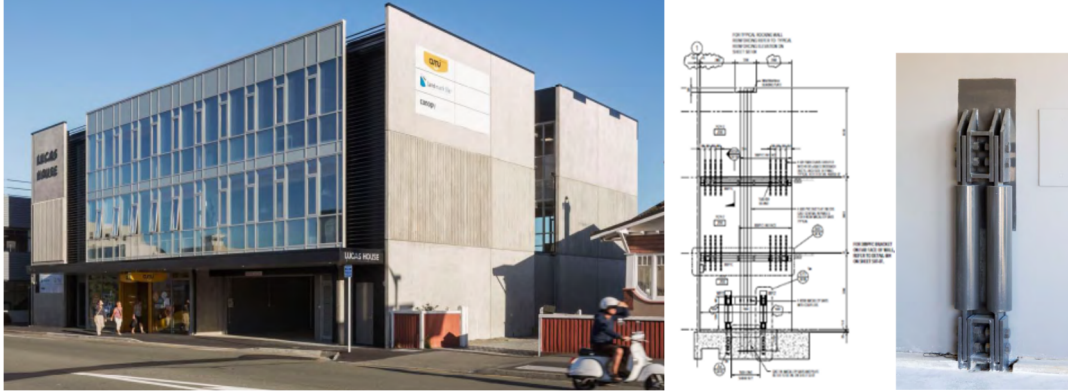
500 Year Earthquake - Force transfer 0.13g and displacement 254mm at a period 2.8 seconds

2,500 Year Earthquake - Force transfer 0.20g, Displacement 520mm at a period 3.3 seconds,

**Possible Repair** – No significant structural damage expected. Sacrificial seismic cover plates and flashings disrupted and will required reinstatement. Limited damage to interior fit-out at ULS is expected due to frame flexibility and drift at ultimate limit state. The building will re-centre due to the bearing curvature. A nominal displacement offset may remain post-earthquake

#### 1.14 Case Study 6 – Lucas House – Nelson

**Description** – 3 Storey commercial office building



Lucas House with post tensioned rocking walls

**Resilient Technology** – Post tensioned rocking precast concrete walls with compression and tension buckling restrained energy dissipaters.

**How it works** – The seismic resisting walls are post tensioned to the foundations and are allowed to rock during a large earthquake. Energy dissipation and damping is provided by plug and play energy dissipaters which are sized to yield in tension and compression during rocking.

**Possible Repair** –Replacement of the sacrificial energy dissipaters will be required if wall rocking occurs.

#### 1.15 Conclusion

Resilient building design has focused on minimizing the level of seismic damage to structures so that buildings may be rapidly reinstated for their purpose after a major earthquake. Examples of these technologies are buildings which incorporate special connection detailing, supplemental energy dissipating devices, rocking systems and base isolation techniques.

Many different types of resilient building designs are emerging in New Zealand as a response to the increased understanding of seismic risk versus building investment. The Christchurch earthquakes have promoted an increased focus and strong uptake of resilient building technologies. The application of non-base isolated resilient building design in New Zealand has been limited to only a few design consultants, as the design methodologies are not yet written into New Zealand codes probably limiting market uptake. Resilient building design information largely resides in research papers and a few publications [3], while freely available, are difficult to implement without prior experience. Close collaboration with universities and researchers is important to successfully deliver a reliable and robust resilient building design.

The cost of resilient design is not well understood in the New Zealand construction market, which adds cost and uncertainty to new developments impacting on the financial feasibility of resilient buildings. Cost is often the deciding factor in determining the degree of resilience applied into a building design. Our experience has shown the non-base isolated resilient building design adds between 1% and 3% to the construction value by comparison with a conventional ductile designed building. Base isolation adds 5% to 7%. The lowest cost premium paid for a non-base isolated resilient building (with the lowest performance, i.e. non re-centring) is through using a replaceable K Brace link (Case study 4). The highest cost premium, also associated with best performance (re-centring), is the implementation of Ringfедder [2] rocking frames (Case study 2) [4]. Base isolated solutions will provide significantly higher performance by comparison to non-base isolated resilient buildings (Case Study 5).

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