Earthquake Protection Technologies for Structural and Non-Structural Applications: Case Studies Worldwide

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ABSTRACT

Seismic hazards pose significant risks to the built environment, demanding effective mitigation measures. In recent years, there has been a surge in seismic control technology development, highlighting its crucial role in earthquake protection. High-level seismic design strategies, such as seismic isolation and vibration control (dampers) designs, have played a vital role in this progress.

This paper provides an overview of earthquake protection technologies, focusing on real-world case studies. It covers applications of seismic isolation in newly constructed and retrofitted buildings in New Zealand, along with the use of non-structural isolation to protect critical equipment and high-value artwork. Additionally, the paper showcases examples of damper applications in seismically isolated and retrofitted buildings, with a particular emphasis on case studies from Japan.

1 INTRODUCTION

Seismic events pose a significant challenge to the structural integrity and safety of buildings, bridges, and critical equipment worldwide. The devastating consequences of earthquakes have prompted continued research and innovation in developing seismic hazard control technologies aimed at mitigating the impact of ground motions on structural and non-structural components. In recent decades, engineers, researchers, and manufacturers of earthquake protection systems have collaborated to devise sophisticated strategies to enhance the resilience of structures against seismic forces. From base isolation and energy dissipation devices to innovative damping systems and advanced structural devices, the arsenal of seismic mitigation strategies continues to expand.

This paper presents an overview of the advancements in seismic hazard control technologies for structural and non-structural applications by demonstrating some real-world case studies from New Zealand and other countries worldwide.

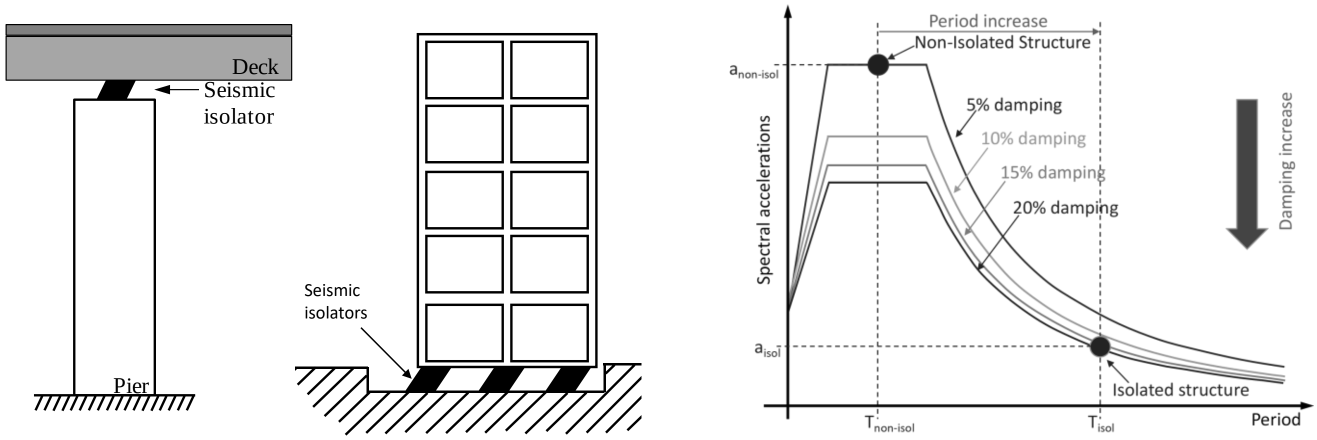


Figure 1: Seismic isolation of bridges and buildings (left) and Reduction of accelerations (right)

2 SEISMIC ISOLATION

Compared to the conventional seismic design, which relies on the ductility of the structural elements to avoid collapse by allowing damage, seismic isolation focuses on decoupling the structure from the earthquake and dissipating seismic energy to reduce induced forces and structural damage.

The seismic isolation of a bridge or building is achieved by increasing the flexibility of the structure with the installation of seismic isolation bearings with low horizontal stiffness (Fig. 1 left). This increases the fundamental period of the structure, avoiding resonance and thus minimizing accelerations and seismic energy transfer to the structure (Fig.1 right). Earthquake-prone countries worldwide, including New Zealand, the USA, Japan, etc., use this cost-effective method for seismic protection. The subsequent sections outline a series of case studies illustrating the application of seismic isolation in buildings in New Zealand, along with examples of non-structural isolation applications to safeguard critical equipment and high-value artwork.

2.1 Parliamentary Library and Parliament House

The Parliamentary Library and Parliament House in New Zealand (Fig. 2) were completed between 1883 and 1922. By the 1980s, the foundation was showing signs of deterioration in both buildings. Given that the buildings were within 400m of the Wellington Fault, the New Zealand Government decided to strengthen and refurbish the buildings while meeting the requirements for the conservation and permanent preservation of the structure (Poole and Clendon 1992). To achieve these objectives, it was decided that the best solution to maximize the retention of original materials and workmanship, avoid changes to the exterior appearance, and provide seismic protection was to retrofit the buildings using base isolation.

Figure 2: Parliamentary Library (left) and Parliament House (right)

Figure 3: Lead rubber bearing (left) and PTFE slider (right)

Figure 4: Old Bank Shopping Arcade Exterior View (left), Ryman Healthcare Center exterior view (center), and Kumutoto Site 10 exterior view (right)

In 1994, 417 base isolator bearings were installed in the existing foundation of the buildings (Parliamentary Service 2011). The isolation system was comprised of lead rubber bearings (LRBs) and rubber bearings (RB), with bearing diameters ranging from 50 to 61 cm., and PTFE sliders.

Lead rubber bearings (Fig. 3 left) are composed of alternating layers of natural rubber bonded to intermediate steel shim plates. A rubber cover is provided to protect the internal rubber layers and steel plates from environmental degradation and corrosion. From a construction perspective, lead rubber bearings differ from rubber bearings only by adding a press-fit lead plug into a central hole in the bearing. The rubber provides horizontal flexibility, while the steel shims provide vertical rigidity for the system. PTFE sliders (Fig. 3 right) contain a stainless-steel backing plate and a flat sliding surface made of PTFE, providing horizontal flexibility and high vertical stiffness.

Although the Parliamentary Library and Parliament House were not subjected to the strong ground motions from the Christchurch earthquakes of 2010 and 2011, the buildings are expected to be fully functional if subjected to an earthquake due to the application of isolation.

2.2 Old Bank Shopping Arcade

Situated in Wellington, New Zealand, the Old Bank Shopping Arcade (Fig. 3 left) underwent a retrofitting process to meet seismic requirements. The integration of base isolation techniques played a pivotal role in aligning the building with stringent seismic requirements, ensuring enhanced structural resilience and safety. The old building was transformed into a shopping plaza after the completion of the retrofit.

In 1997, 109 seismic isolation devices, consisting of 82 LRBs and 27 RBs with a diameter measuring 53 cm, were installed for the retrofit of this building. Although the Old Bank Shopping Arcade has not experienced any major earthquakes since the retrofit, it is believed that this building will be operational during and after a major earthquake.

2.3 Ryman Healthcare

Ryman Healthcare takes the forefront in offering retirement living choices to individuals aged 70 and above in New Zealand. Ryman Healthcare achieves this by intricately designing and constructing communities with high standards and appealing architectural concepts (Fig.4 center). The villages provide a variety of building options and care alternatives, such as independent townhouses and apartments, serviced apartments, and a comprehensive care center.

During the design phase of the building, several alternative structural forms were considered to overcome the seismic demands, including reinforced concrete moment resisting frames, eccentrically braced or concentrically braced frames in structural steel, and buckling restrained brace frames. However, this would require modifications to the architectural layout, impact apartment sizes, increase wall thicknesses, and deeper piled foundations, which would increase cost with longer construction duration. This poses a significant concern for Ryman, especially given the vital importance of adhering to tight construction timelines. Seismic isolation was determined as the optimal solution, effectively addressing all the previously mentioned challenges while ensuring enhanced structural resilience for the building. (Mayes et al., 2016)

This building was constructed with 109 seismic isolation devices in 2015, comprising 67 LRBs with a bearing diameter of 100 cm and 42 PTFE sliders with varying PTFE diameters from 10 to 47 cm.

2.4 Kumutoto Site 10

The Kumutoto Site 10 project (Fig. 4 right) is located at the heart of the Wellington Waterfront, within the Kumutoto Precinct, which is a vital junction connecting the city, port, and waterfront. For this project, base isolation enabled the preservation of the console and architectural details within the structure while meeting the structural design requirements.

In 2016, 66 seismic isolation devices, including 35 LRBs with a bearing diameter of 116 cm and 31 PTFE sliders with a diameter of 37 cm, were used as the isolation system in this building.

2.5 Non-structural Isolation

Non-structural seismic isolation is a technology that protects specific equipment against seismic forces rather than isolating the entire structure (Kasalanati A. et al., 2017). This technology was used in several projects in the United States of America (USA), such as the Dancing Ladies sculpture built on a seismic isolation platform to avoid damage during an earthquake, the Party Hat statue, which was determined as a critical art piece built near the San Andreas fault, and the Computational Research and Theory Facility (CRTF) at the Lawrence Berkeley National Laboratory which houses supercomputers. (Fig. 5)

Figure 5: Non-Structural Isolation

3 SUPPLEMENTAL DAMPING

The conventional approach for the seismic design of structures relies on structural elements' strength, deformability, and energy absorption to resist seismic forces. In other words, structural damage is allowed to absorb seismic energy and prevent structural collapse. To move damage away from the primary structural elements, many buildings in Japan utilize dampers that dissipate most of the seismic energy transmitted to the structure. Based on the mechanism of energy dissipation, dampers can be classified as metallic yielding dampers, friction dampers, viscous wall dampers, or hydraulic cylindrical dampers, e.g., oil dampers.

Viscous Wall Dampers (VWDs) is a technology developed in Japan that is an effective solution for enhancing the seismic performance of buildings by reducing the seismic demands, especially inter-story drifts, without compromising the façade of the building. VWDs have been used mainly in flexible framing systems, such as moment frames, to reduce inter-story drifts and add damping. VWD system was used in more than 100 projects in Japan, one in the USA (Fig. 6), Guatemala, and Mexico (Mohammed et al. 2023).

Oil dampers are hydraulic devices that consist of a piston head contained in a cylinder filled with oil (Fig. 7). Energy is dissipated in the damper by pushing the fluid through an orifice in the piston head. This produces a damping pressure, creating a damping force, and seismic energy is transformed into heat, dissipating into the atmosphere. The damping force is velocity-dependent and follows a bilinear relationship because the fluid flow through the piston is controlled by two sets of relief valves installed in the orifices.

The following sections detail a set of case studies demonstrating the usage of oil dampers in both seismically isolated and fixed-base buildings in Japan.

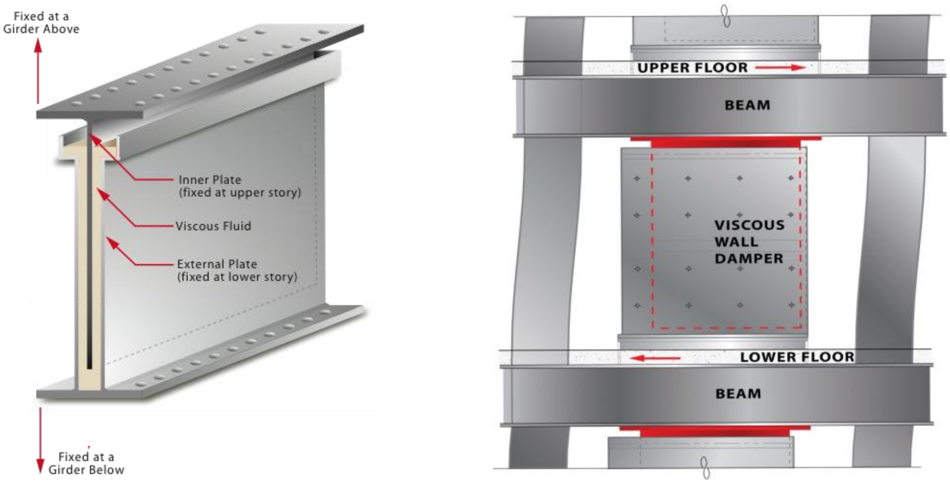
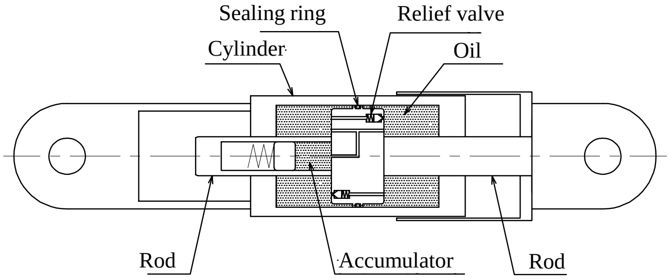


Figure 6: Viscous Wall Damper



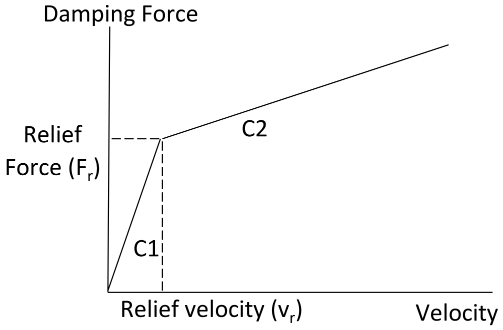


Figure 7: Structure of the oil damper (left) and bilinear force-velocity relationship (right)

3.1 Dampers in seismically isolated buildings: the Toda Green Office Building in Japan

Conventional seismic isolation systems are typically designed with a single device type, such as lead rubber bearings, responsible for all functions of the system—period elongation, energy dissipation, and re-centering. Sometimes, the design process becomes complex and less cost-effective because various factors like bearing diameter, rubber height, lead plug size, etc., affect all those functions. This can limit the design flexibility due to the restrictions in increasing certain features, e.g., damping, without affecting others.

A hybrid isolation system presents an innovative approach by integrating three distinct devices—flat sliders, rubber bearings, and dampers—into the isolation system. This design effectively segregates the functions of an isolation system among different devices and utilizes dampers at the isolation level to achieve high damping levels. Over the past decade, Japan has witnessed a steady rise in adopting hybrid isolation systems. Approximately 25% of newly constructed isolated buildings incorporate dampers (JSSI, 2023). This approach provides enhanced design flexibility and allows supplemental damping to decrease seismic displacements without significantly altering the system's period. The expected benefits include a reduction in displacements, reduced isolator size, or decreased overturning and base shear.

The TODA Green Office building, depicted in Figure 8 and situated in Tsukuba City, north of Tokyo, serves as an illustrative example of a hybrid isolation technology application (Takenaka et al., 2021). Completed in 2023, the structure incorporates a hybrid base isolation system featuring a combination of flat sliders, rubber bearings, and oil dampers. The project integrates two semi-active electronically controlled oil dampers synchronized with seismometers at the isolation level. The dampers are designed with a maximum damping force of 1,000 kN and a maximum stroke of ± 650 mm.

Figure 9 (left) depicts the internal structure of the semi-active dampers developed for the Green Office building. These semi-active dampers utilize electronically controlled valves to modulate the flow of viscous material between reservoirs, thereby adjusting the force-velocity relationship to mitigate seismic displacement while limiting the increase in peak story acceleration. This is done by modifying the damper's primary damping coefficient C1, governing low-velocity performances, by an algorithm based on real-time seismic response data captured by seismometers within the isolated structure. This parameter is adjustable between low damping "CL" (valve open) and high damping "CH" (valve closed) states (Fig. 9 right). While the additional stiffness introduced by oil dampers could be offset by reducing the stiffness of the isolators and the supplemental damping provided, it can be more effectively mitigated using semi-active dampers.

Results from multi-mass model time history analysis (Ishida et al., 2023) show that this semi-active damper system can reduce story displacement in mid-rise and high-rise buildings by up to 20% without amplifying story acceleration compared to an identical system equipped with an equivalent amount of passive dampers.

Figure 8: TODA Green Office building (left) and semi-active oil dampers in the isolation level (right)

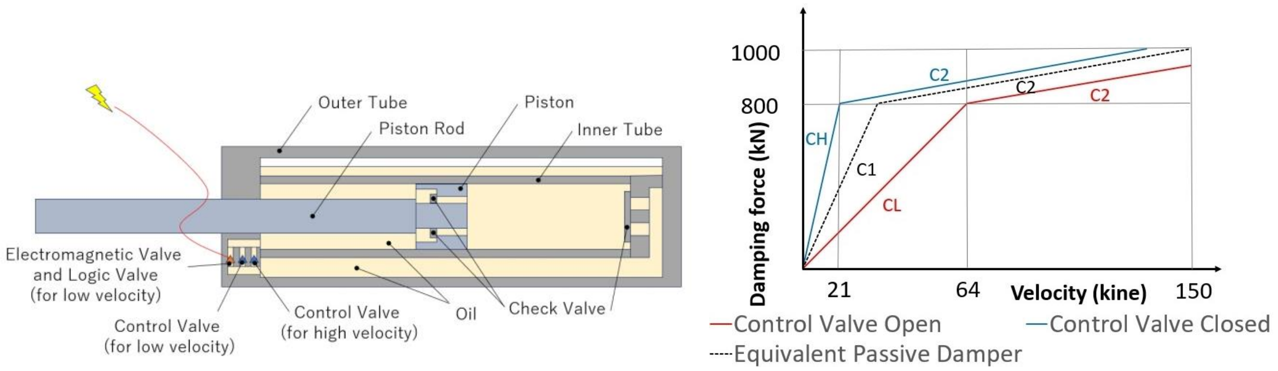


Figure 9: Semi-active damper's structure (left) and force-velocity relationship (right)

3.2 Dampers in fixed-base buildings: the retrofit of a governmental office in Japan

Installing dampers in existing buildings for seismic retrofit purposes can drastically improve the safety and seismic response of the structure. Besides, since dampers can be installed on the façade of the building, the retrofit works could be carried out while maintaining routine business operations with minimal interference.

Dampers can be installed in buildings following different configurations, e.g., as a diagonal brace, as horizontal members in a chevron brace configuration, or in a toggle-brace-damper configuration. The latter configuration features a combination of two braces per damper (Fig. 10). The three elements are connected in one of their ends through a freely rotational pin, while their other end is pin-connected to a beam-column joint of the frame. This damper configuration uses this mechanical connection to obtain displacements in the damper, which are around two times the story drift (Arakawa and Shinbayashi, 2005).

The toggle-brace-damper configuration is especially attractive for seismic retrofit applications, and it has shown its effectiveness in recent strong earthquakes in Japan (Onal, 2020). Figure 11 shows the application of this configuration in the seismic retrofit of a governmental building in Japan (Lopez Gimenez et al., 2020). This 10-story government building is a steel-reinforced concrete (SRC) structure built in 1974 and thus was designed before the introduction of modern and more severe seismic design codes. Due to the importance of this building as a center of coordination in case of a natural disaster in the area, the seismic retrofit of the structure was an urgent and necessary task. It was required to provide a solution that involved minimum interference to the daily activities of the building during the retrofit works and that the retrofit system did not affect the existing louver windows. The maximum allowable inter-story drift was set to 1/150, i.e., 0.67%.

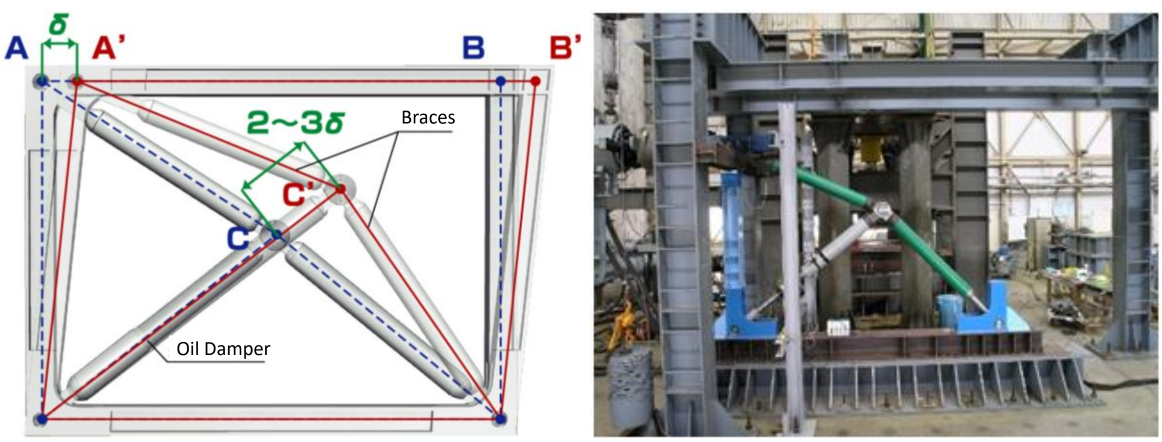


Figure 10: The Toggle-brace-damper System

Figure 11: Governmental Building in Japan with Toggle-Brace-Dampers

After studying several options to reduce the excessive deformations of the original structure to meet these criteria, the installation of oil dampers in a toggle-brace configuration was considered the optimal solution. The use of hysteretic dampers was also evaluated, but the performance criteria could not be met even if these dampers were installed on the whole perimeter of the building. The installation of the toggle-brace-damper system at the façade permitted carrying out the retrofit works without interrupting daily operations. Besides, the amplification factor of the toggle-brace damper reduced the size and the number of locations where the devices had to be installed compared to other damper types or configurations. In total, 248 sets of 500kN-dampers and 60 sets of 800 kN-dampers were installed in the building in 6 months.

4 CONCLUSION

Seismic protection devices, including seismic isolation and dampers, have significantly transformed our approach to mitigating seismic damage, ensuring resilience for structures and their contents worldwide. Seismic isolators and dampers, exemplified by projects in New Zealand, Japan, and beyond, provide significant advantages for both new construction and seismic retrofits by reducing the need for structural modifications, alterations to architectural layouts, and costly foundation changes.

While seismic isolation and dampers are increasingly recognized for their effectiveness, the adoption rate of these technologies remains remarkably low among buildings globally. Several factors contribute to this. Firstly, conventional cost analyses often overlook the long-term savings in life cycle costs associated with these advanced seismic devices, instead focusing only on initial construction expenses. Secondly, implementing new earthquake protective technologies demands practitioners to acquire new knowledge and skills, particularly in nonlinear response analysis, leading to additional design time and effort. Thirdly, the absence of recent damaging earthquakes in certain regions has resulted in a lack of demand for more resilient structures, reducing the incentive to invest in solutions with isolators and dampers. Lastly, in some countries, these seismic protection technologies may not be explicitly addressed in design codes, necessitating alternative compliance pathways. In conclusion, despite the steady growth in applying advanced seismic protection technologies, as described in this paper, challenges still need to be addressed to foster wider adoption of seismic isolation and dampers in building design and construction.

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