Performance comparison of standard and seismic glazing systems

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ABSTRACT

Glazing systems are non-structural elements in a building that, more often than not, appear to be given little consideration in seismic design. Recent experimental work into glazing systems at the University of Canterbury, however, has shown that glazing systems can be very susceptible to serviceability damage, defined as loss of water-tightness. The focus of this paper is to highlight the difference in vulnerability of standard and seismic glazing systems and consider the implications of this for future repair costs and losses. The paper first describes the damage states chosen for glazing units according to the repair strategies required and expected repair costs. This includes three damage states: DS1: Water Leakage, DS2: Gasket Failure and DS3: Frame/Glass Failure. Implementing modern performance-based earthquake engineering, the paper proceeds to highlight a case study comparing costs and expected losses of a standard glazing unit and a seismic glazing unit installed on a case study building. It is shown that the use of seismic glazing units is generally beneficial over time, due to the early onset of serviceability damage in standard glazing units. Finally, the paper provides suggestions for designers aimed at reducing costs related to earthquake induced repairs of glazing.

Keywords: Performance Based, Glazing, Seismic Performance, Fragility, Costs.

1 INTRODUCTION

Recent studies into the seismic performance of glazing systems at the University of Canterbury have shed light into the vulnerability of glazing systems. This opens up the possibility of applying The Pacific Earthquake Engineering Research Performance-Based Earthquake Engineering (PEER-PBEE) framework (Deierlein 2003), shown in Figure 1, to better understand the expected losses of glazing systems. There are many different types of glazing systems available (refer Lago and Sullivan 2012) and a number of studies into the seismic performance of glazing systems have been made (e.g. Behr and Belarbi 1996, Memari et al. 2006, O'Brien et al. 2012, Baird et al. 2014). In New Zealand, common glazing systems could be generalized into three different systems: standard glazing, seismic glazing and structural glazing systems. Issues with the definition of glazing system vulnerability (in New Zealand) are attributed to a lack of mandatory seismic testing and the lack of a standardized seismic design process for manufacturers and engineers to follow. While there are some documentations for designing and/or assessing the life-safety of glazing systems, such as section C10 of The New Zealand Guidelines for The Seismic Assessment of Existing Buildings (MBIE 2017), little attention appears to have been given to the serviceability of glazing systems. Experimental testing recently conducted at the University of Canterbury, however, has shown that standard glazing systems can be very susceptible to serviceability damage. In one of the standard glazing cases tested, it was reported that weathertightness was lost at an inter-storey drift as low as 0.15% (Arifin et al. 2020a).

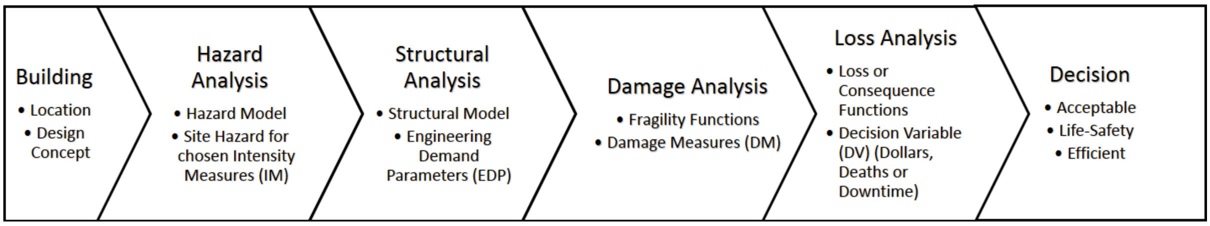


Figure 1: Overview of the PEER-PBEE Framework (Arifin 2018).

Loss of weathertightness may cause further problems with the functionality of a building (mould, damage to linings, etc.). As such, the use of seismic glazing systems is expected to alleviate this problem by delaying the onset of serviceability damage to higher drift values. The downside, however, is increased costs as such system requires more design and material as well as more work to install properly.

In light of the above, this paper endeavours to provide a performance comparison between standard glazing systems in New Zealand and seismic glazing systems in New Zealand. This is achieved by undertaking seismic loss assessment of case study buildings to compare the impact of using either standard or seismic glazing systems on the expected annual losses (EAL). The paper first defines the vulnerability of both glazing systems and explains the difference between the systems. Then a set of consequence functions (loss functions) is also defined based on the damage observed and discussions with industry. Finally, a case study is presented to highlight the performance of each glazing system along with a cost-benefit analysis.

2 VULNERABILITY OF GLAZING SYSTEMS

While there are various types of glazing systems in New Zealand, this paper will only focus on two glazing systems, which are a standard glazing system (Type 1) and a seismic glazing system (Type 2). A standard glazing system only provides deformation capacity via the glass-to-frame clearance (gap) between the framing and the glass, while a seismic glazing system adds another layer of deformation by adding a second frame around the glazing system, referred as the seismic frame, to increase the deformation capacity of the system, as shown in the sketch in Figure 2.

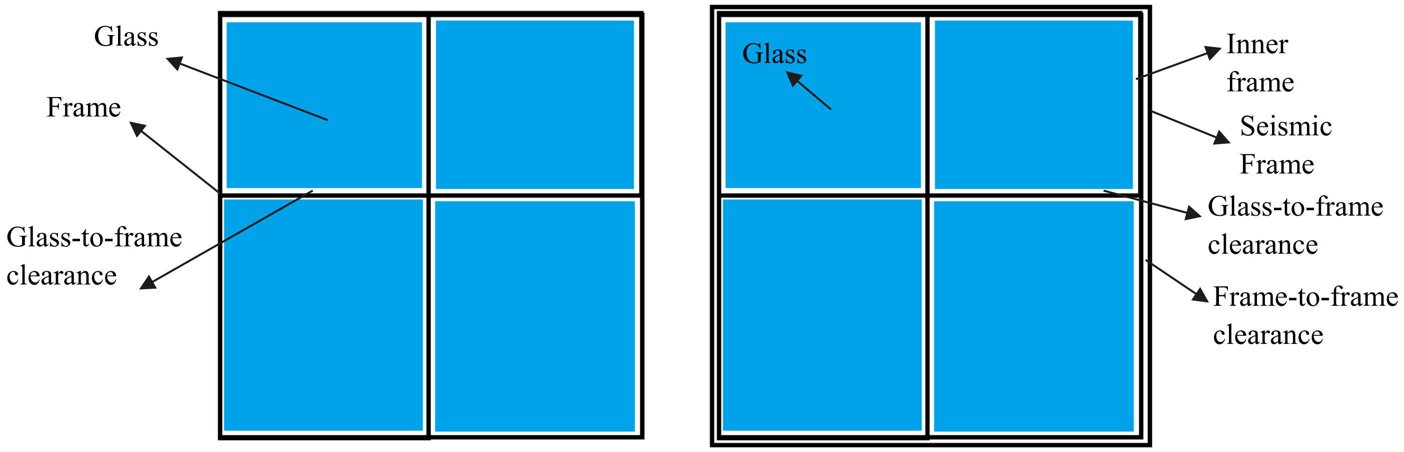


Figure 2: Sketch of the types of glazing systems tested (from left to right): Standard (Type 1) and Seismic (Type 2) (Arifin et al. 2020a).

The seismic frame introduces a frame-to-frame clearance which allows for more in-plane movement of the frame before the system is locked up and the glass is loaded. Figure 3 compares the movement of both systems in a sketch (Type 1 and Type 2).

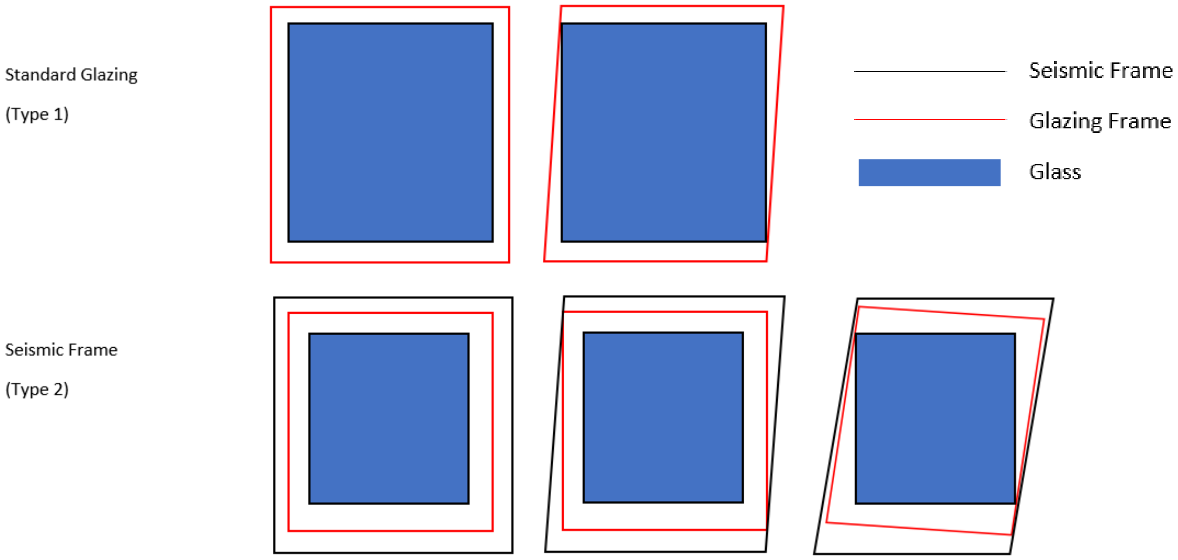


Figure 2: Schematic diagrams depicting the deformation behaviour of glazing system types used in the experimental test (note that after initial contact, the glass pane will also rotate) (Arifin et al. 2020a).

The in-plane movement that occurs during an earthquake and is what causes the glazing system to get damaged. Based on the repair methods required to return functionality to the glazing systems, three damage states have been selected to allow for a vulnerability assessment of the glazing systems (Figure 3):

- Damage State 1 refers to damage causing a loss of serviceability of the glazing system, which is the loss of weathertightness. This would occur when water is observed in locations that it is not supposed to, for example, on the inside face of the glass. The repair strategy includes inspection of sealants and gaskets and reseal where applicable.
- Damage State 2 refers to damage to the gaskets. During an earthquake, the gasket can either “pop-off” from or “dig-in” to its socket which causes further loss of weather tightness and in severe cases, increases the likelihood of glass fallout. While it is rare for the gaskets themselves to get damaged, sometimes the gaskets will require replacement (especially if the gasket age is more than 10 years). Repairing this damage

requires refitting of the gaskets and possibly replacement of the gaskets. In rare cases, the cover beads might also need replacement (cover beads are part of the framing system that holds the "glass-insert" side gaskets, usually the exterior).

- Damage state 3 refers to damage to the glazing system as a whole which will require replacement. This can either be the frame deforming/rupturing or the glass breaking. In reality, if the glass survived the earthquake, it should be reusable. The framing however, more often than not, will require replacement. Furthermore, this damage state poses a life-safety issue as the glass may have fallen out or is no longer secure.

Utilizing these three damage states, the vulnerability of the glazing system can be defined. Describing the vulnerability of a component (fragility) can be done using regression analysis assuming a lognormal distribution as explained in (Porter et al. 2007). This requires at least three data points. As such, three of each type of glazing system was tested according to the experimental protocol explained in Arifin et al. 2020b, and the resulting drifts are shown in Table 1.

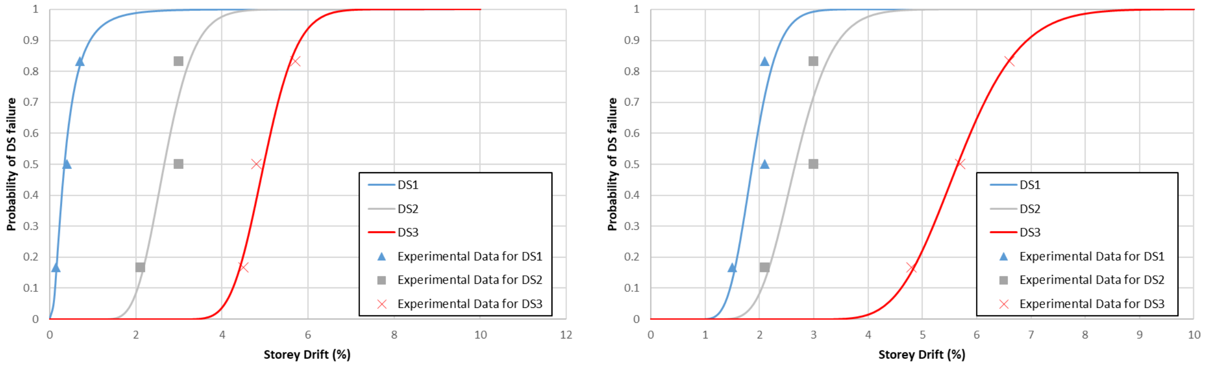
(a) (b) (c)

Figure 3: Damage states (from left to right): (a) DS1 – water leakage, (b) DS2 – gasket failure, (c) DS3 – frame/glass failure.

Table 1: Experimental results, arranged to observe damage states (DS), from testing of glazing systems at the University of Canterbury.

Glazing Type	**Specimen**	**Drift (%)**		
		DS1	DS2	DS3
Standard (Type 1)	1	0.15	2.1	4.8
	2	0.7	3	4.5
	3	0.4	3	5.7
Seismic (Type 2)	4	2.1	3	4.8
	5	1.5	2.1	6.6
	6	2.1	3	5.7

Using the data in Table 1, a regression analysis was run assuming a log normal distribution to create curves that describe the vulnerability (fragility) of the glazing systems. Figure 4 shows the fragility curves obtained for the standard and seismic glazing systems tested.



(a) (b)

Figure 4: Fragility curves for (a) Standard glazing system and (b) Seismic glazing system (Arifin 2020a)

3 GLAZING SYSTEM LOSS FUNCTIONS

As explained in section 2, the vulnerability of glazing systems was defined by the repair strategies needed to retain functionality of glazing systems in buildings. These repair strategies come with a cost to perform such repairs. In reality, the repair costs of glazing systems in New Zealand may vary highly due to uncertainty in the repair work complexity and required scope. However, a consequence function is needed in order to obtain loss estimates of the glazing systems. As such, a generalized glazing consequence function was created with input from manufacturers and engineers in the hopes that these cost estimates will shed light into the importance of seismic glazing units. Note that the approach adopted here is to develop a simplified consequence function that does not incorporate overhead costs associated with the glazing system repair, inspection report costs, landscape, cranes and transport. The cost items considered are described in Table 2.

Table 2: Damage states and simplified generalized repair costs for typical commercial glazing systems obtained via discussion with the industry.

Damage State	**Description**	**Repair work required**	**Cost (per m2 of glazing unit)**		
			Item of Repair	Average Cost (2011 US$)	Disp.
DS1	Water leakage observed (Loss of weathertightness)	Checking of gaskets and sealants Reseal where applicable	1 man-hour labour and materials	7.02	0.5
DS2	Failure of gaskets	Inspection and refitting of gaskets; Replace gaskets if older gaskets are found	4-5 man-hour labour and materials	21.07	0.5
DS3	Frame/glass failure	Replace glazing unit	1 day 2-man labour per unit New unit including framing and glass	42 800.63	0.5

*Note that the average costs are converted to USD in 2011 to match the other cost functions currently in PACT (FEMA 2012).

4 VALUE CASE STUDY

A value proposition is developed to investigate the potential benefits of seismic glazing systems. This is done by applying the PEER-PBEE process to three case buildings. A 4-storey and 12-storey reduced beam section (RBS) building from the QuakeCoRE library which is assumed to be located in Christchurch (Yeow et al. 2018) and a 22-storey eccentrically braced frame (EBF)-building in downtown Christchurch (Arifin et al. 2021). A comparison is done by estimating the expected annual loss (EAL) of each building with the standard glazing system and the seismic glazing system. The expected annual loss is then used as an input for calculating expected loss, which incorporates initial costs. To highlight the magnitude of the losses, only the absolute value of losses is estimated.

4.1 Case Buildings

The first set of case study buildings are taken from a previous study (Yeow et al. 2018). These are buildings, shown in Figure 5, with reduced beam sections (RBS) as the lateral supporting system. The 4 and 12 storey buildings in Christchurch, Auckland and Wellington are labelled as cases 1 through 6. The third building represents a real 22-storey building located in downtown Christchurch, which is labelled as case 7. The building, described in Arifin et al. 2021, is laterally supported with an eccentrically braced frame (EBF) structure. For the purposes of this paper, the cladding of the 22-storey building is assumed to be fully glazed even though the actual building does not have exterior glazing units.

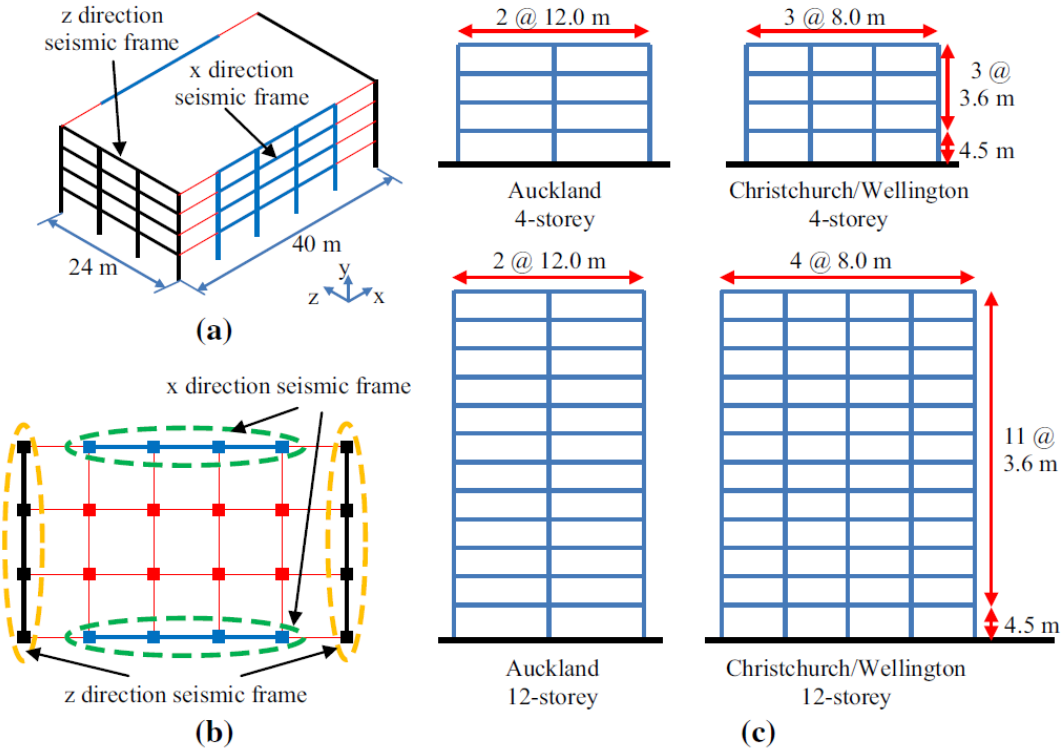


Figure 5: Case study buildings 1 and 2; (a) example of 4-storey isometric view, (b) example of plan view, and (c) frame elevations (modified from Yeow et al. 2018).

4.2 Loss Assessment

All seven cases were run through the FEMA P58 loss assessment process with ground motions selected by Yeow et al. (2018) utilizing the Generalized Conditional Intensity Measure (GCIM) proposed by Bradley (2010) for the Christchurch area (Vs of 200m/s). The hazard model used consists of shaking intensity levels with probabilities of exceedance of 80%, 50%, 20%, 10%, 5%, 2%, 1%, 0.5% and 0.2% in 50 years for each case with spectral accelerations according to each building's fundamental period, as presented in Figure 6. Each intensity level is represented by 20 ground motions that were selected from the NGA database and scaled to fit the demand of each building. These ground motions were used to run non-linear response history analyses (NLRHA) for each building (Cases 1 through 6 was done by Yeow et al. 2018, case 7 by Arifin 2018). Using the resulting engineering demand parameters (EDPs) such as interstorey drift and peak floor acceleration, the vulnerability of the building components can be calculated. Next, the expected annual loss can be estimated via a double integration of the annual probability of repair cost with the mean annual frequency of exceedance (MAFE) of each intensity level (refer to Arifin et al. 2020c). The loss assessment was run twice, in PACT (FEMA 2012), for each case, firstly with the standard glazing system fragility and then with the seismic variant.

Note that the building library (component inventory), fragility and consequence functions of other components for cases 1- 6 was taken from QuakeCoRE Project 17137 (2018) and case 7 from Arifin 2018.

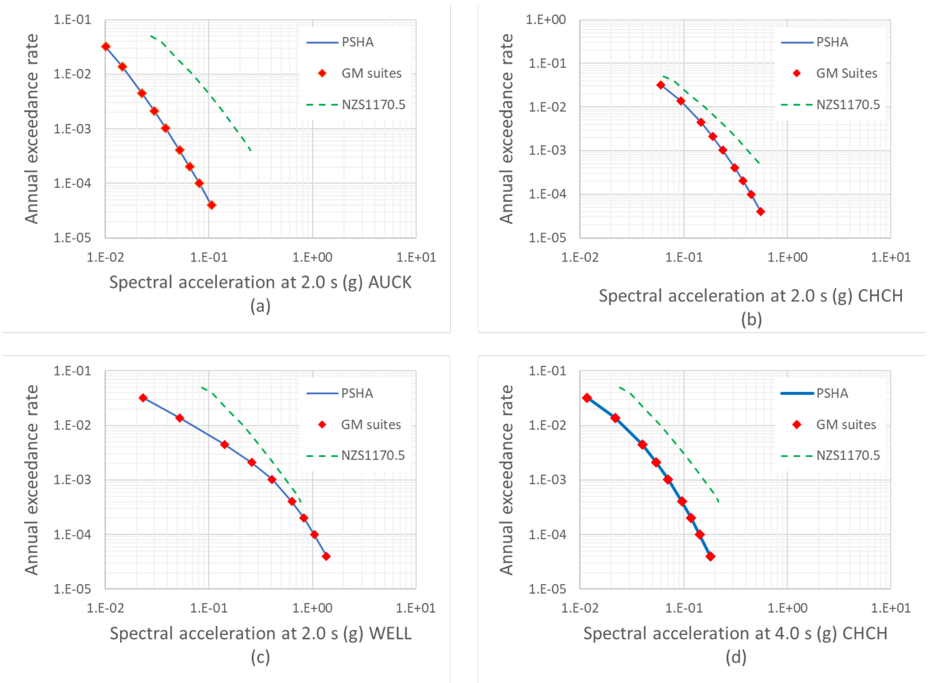


Figure 6: Hazard representation used for (a) case 1-2, (b) case 3-4, (c) case 5-6, and (d) case 7.

Note that the hazard provided by the New Zealand Standard 2004 (NZS1170.5:2004) is considerably different than those obtained through probabilistic seismic hazard analysis (PSHA) (Baker 2008). This could result in different EDPs which also results in different EALs.

The resulting EAL for each case is then used for a cost-benefit analysis by comparing expected losses for each case over 50 years. The expected losses over 50 years can be calculated using Equation 1 (modified from Kappos and Dimitrakopoulos 2008),

$$\boldsymbol{E[C(t)] = C_0 + \frac{1-e^{-\lambda t}}{\lambda}} \cdot EAL \tag{1}$$

Where, $E[C(t)]$ = Expected loss for a given period (t (Years)); C_0= Initial Costs ($); λ= Discount Rate (%); EAL= Expected Annual Loss

5 RESULTS

While the cost functions suggested in section 3 are simplified and require further research and additional validation, an initial comparison between standard and seismic glazing units provides an indication of the additional implementation costs one should be prepared to pay for a seismic glazing system. This cost is referred to here as the break-even implementation costs difference. Table 3 shows the expected annual costs of each case with the standard glazing and seismic glazing and shows the break-even implementation cost difference for a 25-year return on investment. Assuming a discount rate of 4%, the expected loss values were calculated using Equation 1. The break-even implementation cost differences were solved to obtain an ROI of 25 years. Note that, as explained in section 3, these costs have not considered overhead costs, inspection reports, crane, traffic management, etc. and hence, the actual additional expenditure one could deem worthwhile for seismic glazing systems is likely to be higher than shown in Table 2.

Table 3: Expected annual losses for each case and break-even implementation cost differences.

Case	**Location**	**Height (Storey)**	**EAL (NZD)**		**Break-even implementation cost difference for 25-year ROI (NZD/m^2)**
			Standard	**Seismic**	
1	AUCK	4	3439	3262	2.39
2	AUCK	12	5138	4809	1.49
3	CHCH	4	24759	24272	6.60
4	CHCH	12	52302	51270	4.67
5	WELL	4	27434	27047	5.26
6	WELL	12	53774	52846	4.20
7	CHCH	22	25781	24857	3.20

6 CONCLUSION

This paper has conducted research into the potential benefits of seismic glazing systems compared to standard glazing systems. The focus has been to provide stakeholders (designers, manufacturers, etc.) with information to aid in decision making. The paper first described the vulnerability of glazing systems and common glazing system archetypes used in New Zealand. It was reported that the onset of serviceability damage can occur at storey drift levels as low as 0.15% for non-seismic glazing systems but was 1.5% or more for seismic glazing systems. As such, to provide a value proposition towards seismic glazing systems, a cost-benefit analyses comparing standard glazing systems to seismic glazing systems was completed. This required an estimate of the repair costs for different glazing damage states, which were obtained through consultation with the industry. The results show that if the added implementation costs are limited, seismic glazing systems are likely to be beneficial, especially in active seismic areas such as Christchurch and Wellington. Interestingly, the break-even implementation cost differences were found to be relatively low but would increase if additional sources of loss (such as repair complexity or damage to linings) were included and hence, further research into the expected repair cost of glazing systems is still needed.

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