EXPERIMENTAL INVESTIGATIONS INTO THE FRAGILITY OF COMMERCIAL GLAZING SYSTEMS IN NEW ZEALAND

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Abstract

Probabilistic assessment methods, such as those described in the FEMA P-58 framework, underpin modern performance-based earthquake engineering. Such assessment permits quantification of useful seismic risk metrics, such as the expected annual loss and the annual probability of collapse. However, in order to undertake probabilistic seismic assessment, a large amount of information is required, including data on the fragility of building components. This work describes experimental investigations that have recently been undertaken in New Zealand aimed at establishing the fragility of common commercial glazing systems. In-plane full scale quasi-static cyclic testing has been undertaken on three sets of two types of commercial glazing systems, with the objective of establishing the drift at which water resistance is lost and the drift at which the structural integrity of the glazing is lost. The experimental test set-up, including instrumentation layouts and loading protocols, is first described. Subsequently, the damage observed at different levels of drift is reported and discussed. It is shown that the glazing units have relatively high life-safety drift capacity compared to other non-structural elements, but potentially low serviceability capacity. There is also significant variation between glazing typologies that depends on the glass-framing connection detailing. Preliminary fragility functions are formed using the experimental data from the testing. The last part of the paper explains how the experimental test results are being used to calibrate numerical models for the purposes of conducting parametric studies of such glazing systems. Such parametric studies will permit the impact of a broad range of parameters on the seismic fragility of glazing to be assessed, as part of future research.

Keywords: non-structural elements; glazing; fragility; experimental testing

1. Introduction

Advanced performance-based earthquake engineering has opened the possibility to predict economic losses of buildings due to earthquakes through probabilistic assessment methods. As such, it is possible to better understand the impact of mild, moderate and severe earthquake events. This can be achieved through the study of the vulnerability (fragility) of buildings and their components. A study of vulnerability can range from the scale of a simple single component to a full complex building. A significant amount of data, such as the cost of repair, inventory of a building, location, etc., is required to undertake seismic loss estimation. Hence, it is vital to build a library of data for such purposes.

Previous cost related research [1] has highlighted the importance of non-structural elements (NSEs) in reducing losses due to earthquakes, as NSEs contribute to approximately 70% of the total building cost. This work focuses on the vulnerability of glazing systems in New Zealand via experimental and numerical investigations. Glazing systems are common non-structural components that may be vulnerable and increase earthquake risk. A few reports [2, 3] have shown that poorly designed glazing systems may get damaged in an earthquake resulting in glass falling hazard, as presented in Fig. 1.

Fig. 1 – Photos of glazing system fallout during the September 4th, 2010 Darfield earthquake [2] and the February 22nd, 2011 Christchurch earthquake [3].

Unfortunately, direct and indirect losses associated with glazing systems are not well documented in New Zealand. The New Zealand Ministry of Business, Innovation & Employment (MBIE) has provided guidelines that include seismic assessment of glazing systems [4]. This guideline, however, is specific to the life-safety limit (ULS) of curtain walls and has not been extensively studied. While there have been previous research efforts into the seismic performance of glazing systems in New Zealand [5, 6, 7], there are no clear design or assessment limits. Moreover, past research focused mainly on the life-safety performance of glazing systems without detailed evaluation of the serviceability limit (such as weather tightness) state (SLS) performance. Stakeholders might expect that the seismic performance of a glazing system following during a mild to moderate event is good while, in reality, they may lack information of its seismic serviceability performance. This is due to the indistinguishable visual difference between performance levels. An undamaged glazing system may have small deformations within its panels and/or sealants which may cause water leakage. Loss of serviceability performance may cause further damage, for example water leakage can cause mold to form, which will increase costs due to repair and downtime. Seismic glazing systems are designed to postpone SLS damage to higher intensity events and thus are more expensive. However, there is little evidence of any benefits of using such glazing systems, making it difficult to encourage specifiers and owners to use such systems.

In light of the above, research into the seismic performance of glazing systems, for both life-safety and serviceability, is currently being conducted at the University of Canterbury, New Zealand. The research aim is to advance the state-of-the-art of glazing system design and assessment by gaining insight into the seismic performance of glazing systems. One of the biggest challenges is to design an experimental test that is capable of testing both the serviceability limit state (SLS) and ultimate limit state (ULS) while remaining practical to implement. The long-term goal is to have a vast library of fragility functions to advance options for performance-based earthquake engineering. However, due to time and economic reasons, it is not considered feasible to conduct rigorous experimental testing for all types of glazing systems. As such, a numerical approach is planned in a next phase of the project in order to broaden the study.

This paper firstly explains the experimental test approach used to obtain the first few fragilities of glazing systems. This experimental procedure is capable of evaluating both ULS and SLS performance levels. The paper then proceeds to show the benefit of seismic glazing systems compared to conventional glazing systems, highlighting the SLS performance. The final part of the paper elaborates on plans to iterate a numerical analysis approach, which will be calibrated to the first few experiments, in a parametric study to create a broader library of fragility functions.

2. Experimental Testing Procedure

New Zealand Standard NZS4284 [8] includes specifications for the seismic testing of facades. This seismic testing is done by loading the glazing system in-plane to evaluate the system's performance. However, it requires high-speed testing and specific apparatus for air and water penetration tests. After consulting with the industry, it was found that the seismic testing is generally not practical due to the high-speed requirements. Furthermore, the difference in high-speed and standard quasi-static cyclic tests were not considered to be significant (although this also depends on sealant type). As such, a more practical but useful testing procedure needs to be designed to encourage more testing in practice. To increase the applicability even further, it may be possible to relate water penetration and air infiltration, as shown by [9].

Based on the observations above, an experimental testing procedure has been developed at the University of Canterbury (refer to Fig. 2-3). The experimental testing for the seismic performance of glazing systems designed in this research involves two main structures; the main rig, where the glazing systems are mounted and a weather simulator "box" to allow for water penetration testing. The main rig is constructed of two concrete slabs to simulate building floors with a storey height of 3.6m. These concrete slabs are supported by two steel frames that are pinned in the longitudinal (in-plane glazing) direction and are prevented from moving in the orthogonal direction. The rig is connected to a hydraulic actuator which can provide +/- 300mm roof displacement and 800kN of force. The bottom slab is equipped with 200mm concrete "upstands" to allow for the installation of glazing systems and assist the attachment of the weather box (explained below). The concrete upstand is flanked by two steel columns that are also pinned in the longitudinal direction and are restrained from moving in the orthogonal direction. The purpose of these steel columns is to simulate building columns creating an "opening" for glazing systems to be installed.

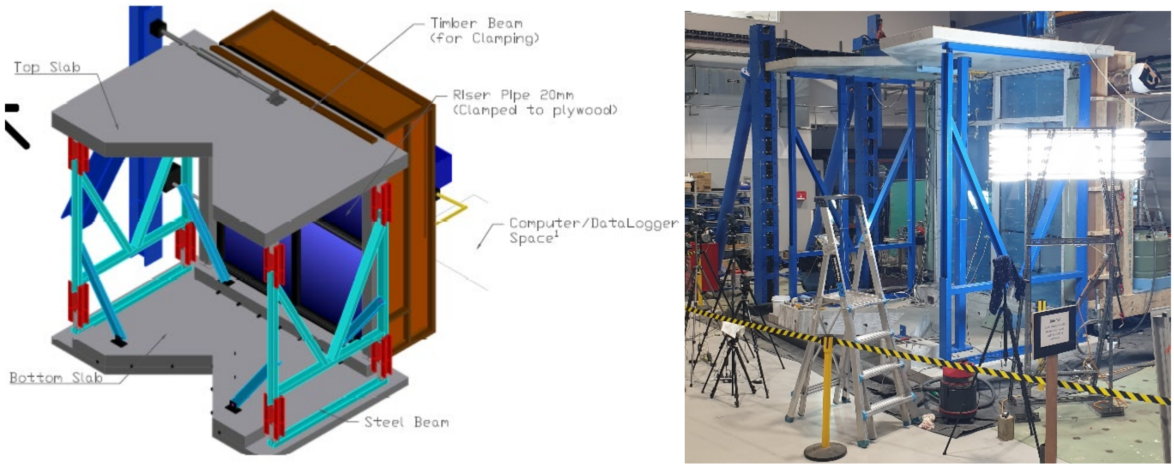


Fig. 2 – Experimental set-up for testing of glazing systems in commercial buildings; showing concrete slabs, support frames, timber box and glazing specimen. Conceptual (left) and Realization (right).

Fig. 3 – Photo of water box, actuator, reaction frame and ram.

The weather box, illustrated in Fig. 4, is built with timber framing and is waterproofed with a fiberglass and paint membrane. In order to simulate weather, the box is equipped with wide spray nozzles, an air blower and two air bleeding valves to control the air pressure inside the box. The spray nozzles are setup 1800mm apart and are mounted 900mm away from the glazing system as shown in Fig. 4. This is done according to recommendations in NZS4211 [10]. Water is then pumped from a water reservoir through the nozzles at 800kPa/32.4lpm (based on New Zealand recommendations) onto the glazing system to simulate rain. Note that the water is recycled through a sump connected with a drainage pump which is connected back to the water reservoir. The air blower, shown in Fig. 5, is utilized to simulate wind conditions in buildings by increasing the air pressure (to a maximum of 600Pa) inside the box, which is controlled via the two bleeding valves and is monitored through a differential pressure sensor.

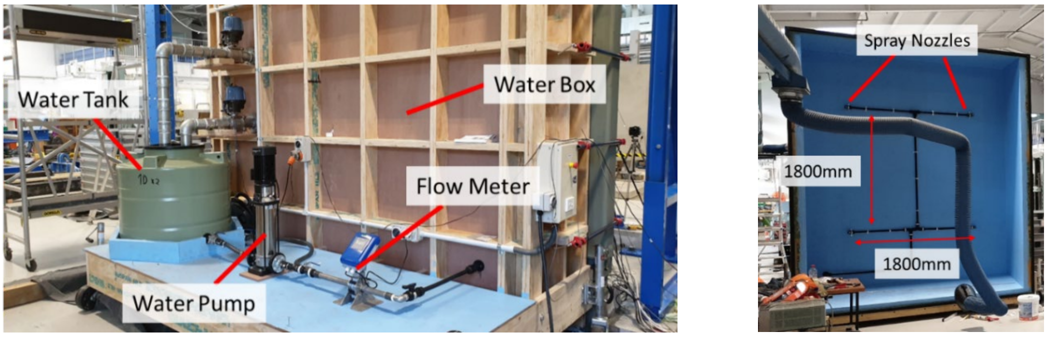


Fig. 4 – Photos of the (a) Weather box (viewed from rear) and equipment for water testing, (b) Spray nozzles inside the weather box.

Fig. 5 – Photos of the air control unit consisting of: air blower (left); differential pressure sensor (middle); bleeding valves (right).

One side of the weather box is open and is surrounded by neoprene foam, as illustrated in Fig.4, which will create a weather-tight seal with the glazing unit during the water-testing. To ensure a weather tight seal, the top and sides of the box are clamped onto the concrete slab and steel columns while the bottom of the box is equipped with threaded rods which are fitted into predrilled holes on the concrete upstand and bolted on the other side, as shown in Fig. 6. The box is also mounted on wheels to ease access and movement during testing. This allows for the weather box to be "attached" for water testing and "detached" for seismic testing.

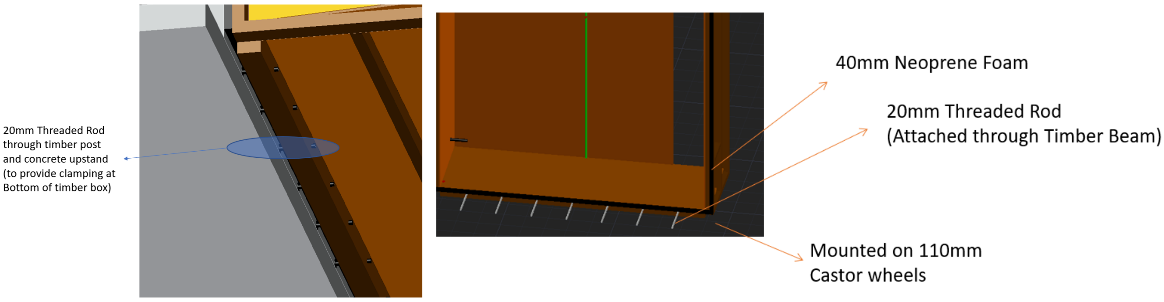


Fig. 6 – Sketch of the weather box showing threaded rods "fitted" into predrilled holes in the concrete upstand and bolted on the other side to provide a clamping force on to the bottom neoprene foam.

Two types of glazing systems, as illustrated in Fig. 7, are tested on the rig. The first (Type 1) is a standard dry-glazed typical New Zealand curtain wall with glass-to-frame clearance and the second (Type 2) specimen has a seismic frame installed around the dry-glazed unit with a clearance.

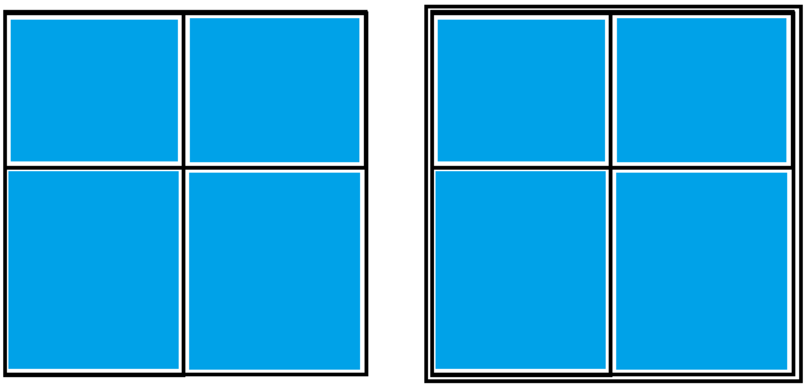


Fig. 7 – Sketch of the types of glazing systems tested (from left to right): Standard (Type 1), Seismic Frame (Type 2).

The main difference between the two specimen types is the deformation behavior. Type 1 only has the glass-to-frame clearance (of 16mm) and once the clearance has been used up the glass locks up and starts pushing on the frame. Type 2 has two clearances which are the seismic frame-to-frame clearance (16mm) and glass-to-frame clearance (10mm). This allows for some movement between the seismic frame and the glazing frame before the glazing frame starts to deform (refer to Fig. 8).

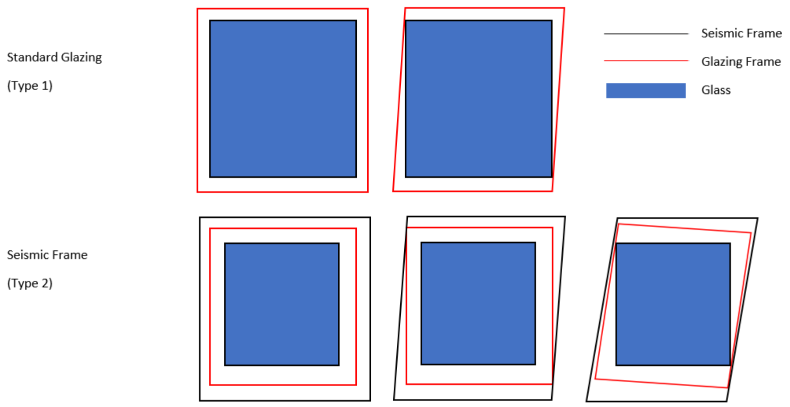
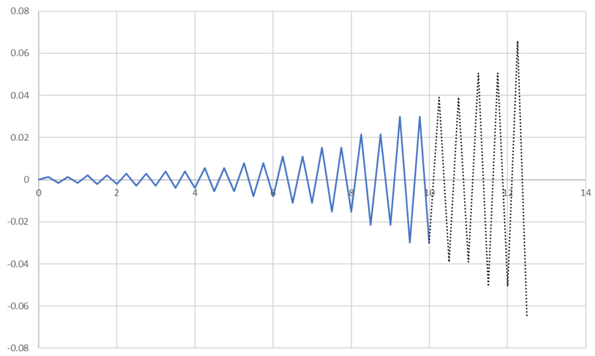


Fig. 8 – Schematic diagrams depicting the deformation behavior of glazing system types used in the experimental test.

Note that Fig. 8 only shows one panel, however, the overall behavior is similar even if the number of panels increases. For this experiment, there are four panels for each specimen. Two bottom panels with small aspect ratios (approximately 0.5) and two top panels with large aspect ratios (approximately 2, refer to [11] for details).

Due to the need for SLS and ULS testing, the testing procedure is divided in two phases; the SLS testing phase and ULS testing phase. The seismic testing follows a loading protocol provided by FEMA 461 [12] with a target drift of 3% obtained in 10 full steps (one full step is comprised of two positive and two negative alternating cycles) as illustrated in Fig. 9. Before testing begins, the weather box is first attached onto the main rig. In the SLS testing phase, the specimen is initially run through a water test to ensure that there are no construction defects. Then, the weather box is then detached before proceeding with a seismic test at the first step of the loading protocol. After returning the rig to zero-roof displacement, the weather box is reattached onto the rig and another water test is done. This process is repeated until leakage has been observed. Leakage is taken as defined in section 9.4 of the NZS4284.



$\Delta_0 = 0.00145$

$\Delta_m = 0.03$

$N = 10$

Fig. 9 – A graph showing the drift demand following the Loading Protocol based on FEMA 461.

Once leakage is discovered, the test proceeds to the ULS testing phase. In the ULS testing phase, the specimen only undergoes seismic testing until collapse without water penetration testing. The complete testing procedure is explained in Fig. 10.

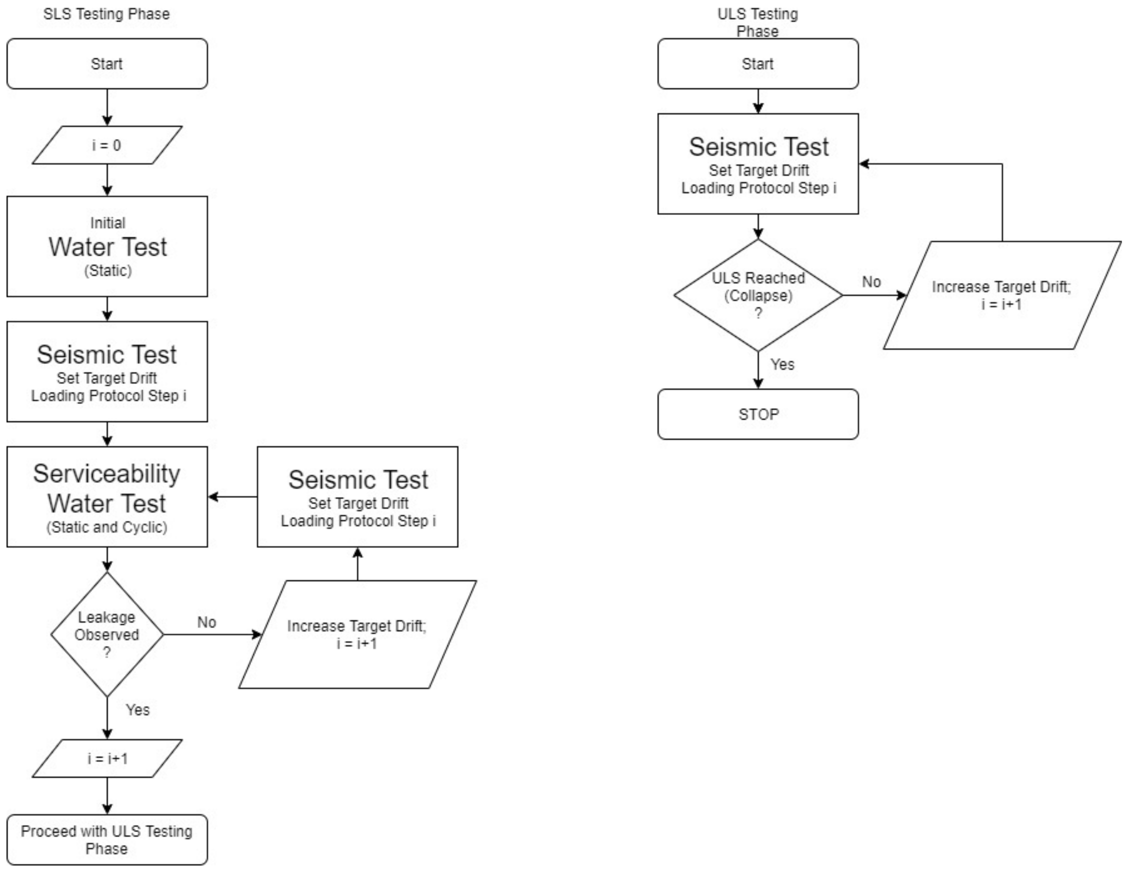


Fig. 10 – A diagram showing the testing procedure for both SLS and ULS testing phases.

Apart from the roof-displacement measurement via a potentiometer, the total force entering the system is also measured using a loadcell attached to the hydraulic actuator. Furthermore, to evaluate the behavior of the glass and frame, eight potentiometers were installed on the glass to measure the deformation between the glass and aluminum frame, the locations of the potentiometers can be seen in Fig. 11. Particle Velocimetry Tracking (PTV) [13] is also used in conjunction with the glass potentiometers to better understand the behavior of the glass and aluminum frame. Note that visual inspection is also used as means of data collection as the water penetration test requires a pass-fail system which is done by such visual inspections.

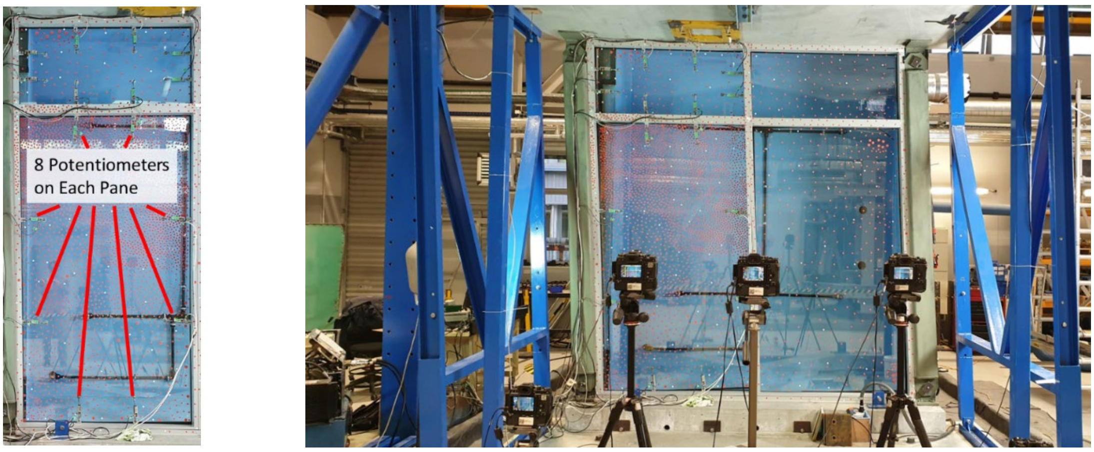


Fig. 11 – Photo showing glazing specimen and instrumentation used in the experimental testing, showing cameras and red dots used for particle-tracking (left) and potentiometers used to monitor displacements of panes relative to framing (right).

3. Experimental Results: Comparison Between Systems

Following the testing procedure explained in section 2, the findings show that there are three main "damage states" that would require repair costs for a typical glazing system. These three damage states are:

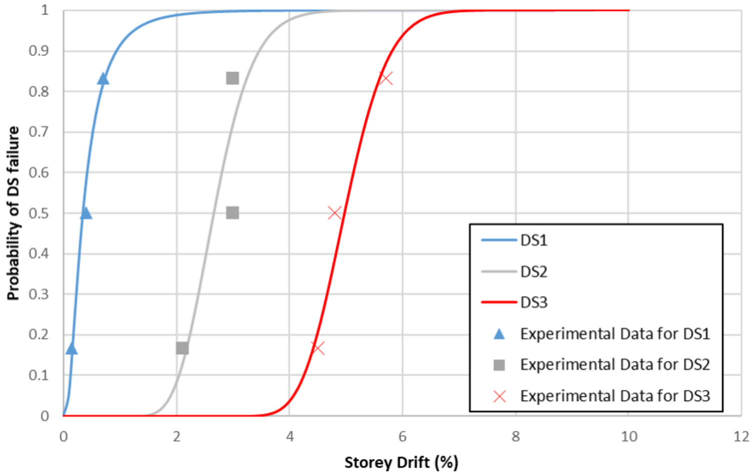
- DS1: loss of the water-tightness of glazing units, judged to occur when water first appeared on the inside face of the glazing;
  - Requires inspection of sealants and gaskets and possibly refitting of gaskets;
  - May cause further serviceability damage such as mold forming, moisture increase, etc.
- DS2: visual gasket failure in which gaskets were seen to have moved out of place (either jammed into framing or falling out) and would have prompted repair;
  - Requires repair of gaskets (pulling out jammed gaskets, pushing in fallen out gaskets);
  - May need to replace gaskets that have fallen out (or jammed in);
  - Some framing components might also need replacement, especially the gasket cover (beads).
- DS3: failure of the glass (either significant cracking or fall-out);
  - Requires replacement of the glazing system.

Based on the three damage states recorded, a summary of the results is reported in Table 1. It has been observed that for DS1, the damage occurred in the bottom panels, which shows that aspect ratio has a significant role in the behavior of glass panels. While for DS2 and DS3 there are no specific locations for the initial damage.

Table 1 – Experimental results showing date of testing, damage states observed, and forces recorded

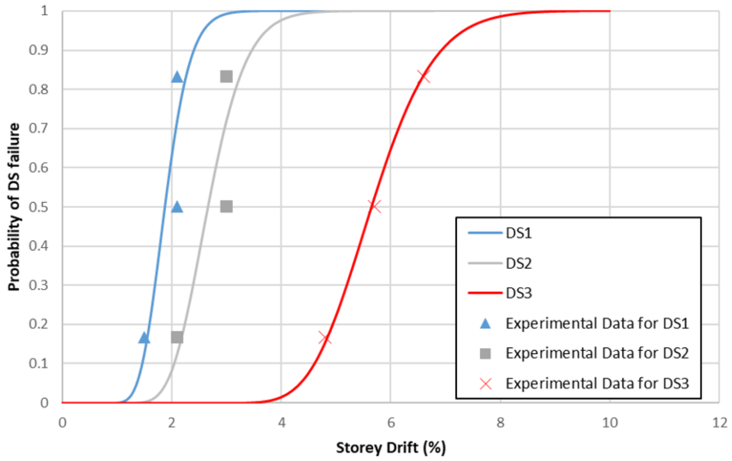
Glazing Type	Specimen #	Date	DS1		DS2		DS3	
			Drift (%)	Force (kN)	Drift (%)	Force (kN)	Drift (%)	Force (kN)
1	1	October 4th, 2019	0.15	1.2	2.1	2.2	4.8	8.4
	2	October 17th, 2019	0.7	1.3	3.0	1.4	4.5	7.7
	3	October 29th, 2019	0.4	1.8	3.0	2.5	5.7	10.0
2	4	November 5th, 2019	2.1	2.75	3	2.72	4.8	9.76
	5	November 19th, 2019	1.5	2.05	2.1	2.05	6.6	8.53
	6	December 2nd, 2019	2.1	5.48	3	5.23	5.7	8.72

Using this data, fragility curves can be estimated for each type via a regression analysis assuming a lognormal distribution as shown in [14]. These fragility curves are shown in Fig. 12.



	xm	b
DS1	0.35	0.78
DS2	2.66	0.21
DS3	4.97	0.12

(a)



	xm	b
DS1	1.88	0.19
DS2	2.66	0.21
DS3	6.6	0

(b)

Fig. 12 – Graphs showing fragility curves for (a) Type 1 and (b) Type 2 along with tables showing the median drift and dispersion.

Based on the fragility curves presented above, it was found that both types of glazing system performed similarly in the ultimate limit state as both systems exceeded the target design (3% Drift). However, the SLS performance of Type 1 was vastly outperformed by Type 2. Leakage was observed as early as 0.15% drift, with a median of 0.35% drift with Type 1 while Type 2 did not fail the SLS test until 1.5% drift (median of 1.88% drift). Note that the dispersion of DS1 Type 1 is 0.78. This is attributed to the uncertainties in installation that significantly affects the weather-tightness of the system. For example, the installers may have installed the glazing slightly off-center, which may increase early rotations of the glass. Unfortunately, due to the lack of standardized glazing systems, there is a wide variety of glazing system practices in New Zealand. This would be expected to increase the uncertainty even further.

4. Future Work: Numerical Analyses and Parametric Study

As mentioned in section 1, future work will look to increase the variety of glazing systems via a parametric study utilizing numerical models which will be calibrated with the experimental testing results. The result of the parametric study will be a broad range of fragility functions for different configurations of glazing system.

The numerical model will be based on [15] with finite elements used to model the glass behavior. The parametric study will cover a range of parameters as shown in Table 2.

Table 2 – Parameters for future work parametric studies

Variable	Model Code	Values (#)									
Aspect Ratio	AR#	0.2	0.25	0.33	0.4	0.5	0.67	1	2	1.5	3
Configuration	CO#	1x1		1x2		1x3		1x4		1x5	
		2x1		2x2		2x3		2x4		2x5	
		3x1		3x3		3x3		3x4		3x5	
		4x1		4x2		4x3		4x4		4x5	
		5x1		5x2		5x3		5x4		5x5	
Clearance (mm)	CR#	5	10	16	20						
Glass Thickness (mm)	GT#	3	4	6	8	10					
Glazed Unit	GU#	Single(1)			Double (2)						
Connection Type	CT#	Standard (std)			Seismic (smc)			Structural Silicone (str)			

5. Conclusions

This paper has detailed the on-going experimental testing procedure developed at the University of Canterbury which is capable of evaluating both SLS and ULS seismic performance of glazing systems. The experimental procedure is practice-oriented and may increase specification of seismic glazing testing in New Zealand. By removing the requirement for high-speed testing and air penetration tests, the procedure is simpler but is still considered effective. Note that further considerations on the slippage of sealant that are sensitive to velocity must be made for specific glazing systems.

Utilizing the experimental set-up, testing of two different types of curtain wall glazing systems have been done and their respective results shown. The results have shed light into the SLS performance of glazing systems and the fact that there are minimum specifications for SLS performance. While the results indicate that both systems have good life-safety performance, the serviceability performance of the seismic glazing system (Type 2) vastly outperforms the standard glazing system (Type 1). Hence, to the results motivate the use of seismic glazing systems as they could delay the onset of water damage, which will delay further damage, such as mould etc. In the long run, such systems are beneficial, as SLS damage may be indistinguishable until it is too late and requires cost due to repairs and downtime.

This research acknowledges the large variety of glazing systems practice owing to the lack of a standardized glazing design. The current results only provide an indication of the seismic performance of glazing systems. As such, future work on broadening the sample size (through experimental and numerical analyses) is planned.

6. Acknowledgements

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