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# Developing guidelines for the seismic assessment of glazing systems

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## **ABSTRACT**

There is an increasing recognition that the seismic performance of buildings will be affected by the behaviour of both structural and non-structural elements. In light of this, work has been progressing at the University of Canterbury to develop guidelines for the seismic assessment of commercial glazing systems. This paper reviews the seismic assessment guidelines prescribed in Section C10 of the MBIE building assessment guidelines. Subsequently, the C10 approach is used to assess the drift capacity of a number of glazing units recently tested at the University of Canterbury.

Comparing the predicted and observed drift capacities, it would appear that the C10 guidelines may lead to non-conservative estimates of drift capacity. Furthermore, the experimental results indicate that water-tightness may be lost at very low drift demands, suggesting that guidance for the assessment of serviceability performance would also be beneficial. As such, it is proposed that improved guidance be provided to assist engineers in considering the possible impact that glazing could have on the structural response of a building in a large earthquake.

## **1 INTRODUCTION**

Recent events, such as the 2016 Kaikōura earthquake and the 2010-2011 Canterbury earthquakes, have highlighted the damage earthquakes cause to glazing systems (Dhakal 2010, Baird et al. 2011). Figure 1 illustrates damage to glazing observed from the Canterbury earthquakes. Photos in the press (Stuff, 2017) of shattered glass on footpaths and reports that areas may be cordoned off because of the risk posed by falling glass remind us that the performance of glass windows/glazing in earthquakes can be a life-safety matter. There were many reports of injuries due to broken glass lying in egress routes following the Canterbury earthquakes. In addition, the repair of glass facades can be costly and time-consuming and accessibility to damaged parts can pose a significant challenge in many cases. Following the Kaikōura earthquake, due to the complexity of the repair work (including access) glazing repairs in downtown Wellington reportedly cost as much as \$50,000 per pane (Valli, 2017).



*Figure 1. Examples of glazing damage that occurred in the September 4th 2010 Darfield earthquake (Dhakal 2010) and the February 22nd 2011 Christchurch earthquake (Baird et al. 2011).*

Despite the apparent issues associated with poor performance of glazing in earthquakes, the New Zealand engineering community has a relatively limited amount of information available for the assessment of such risks. Research undertaken by BRANZ (Thurston and King 1992, Lim and King 1991, Wright 1989) provides useful insight into issues facing the seismic performance of glazing systems and details a testing procedure to evaluate the racking capacity of curtain wall glazing. However, the information provided in these reports has not translated into clear deformation limits or guidelines for engineers to assess the capacity of glazing systems for different performance/damage states. Section C10 of the MBIE guidelines for building seismic assessment (MBIE, 2017) does identify that glazing may fall if there is damage to curtain wall framing systems, and yet expressions included in C10 for the drift capacity do not appear to have been rigorously verified.

While some guidance for life-safety assessment of glazing is provided by the C10 guidelines, there appears to be a lack of literature related to the assessment of serviceability capacity. Serviceability performance measures such as water-tightness and airtightness are important requirements for glazing, and the failure to maintain either of them may cause economic loss due to repairs and downtime (Sullivan, 2020).

Unfortunately, as will be shown in this paper, such failures may be going unnoticed as performance will not be well judged purely from on visual signs of damage.

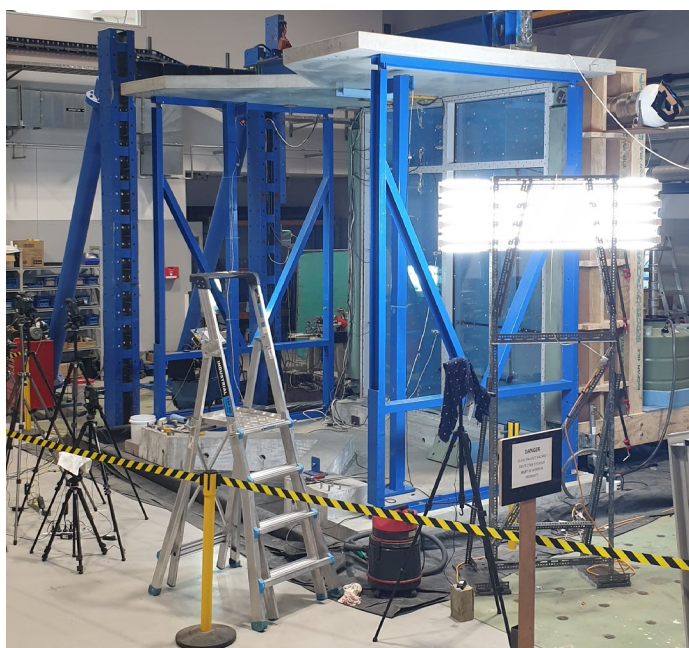
In light of the above, research into the seismic performance of commercial glazing systems has been proceeding at the University of Canterbury over the past two years. The focus of this paper is to investigate the seismic assessment provisions for glazing systems provided by the New Zealand Guidelines for The Seismic Assessment of Existing Buildings (MBIE, 2017). This paper first describes the experimental testing set-up developed at the University of Canterbury, then details the damage observed and finally, a comparison between the performance prediction obtained implementing current assessments procedures with the experimental response observed in a series of experimental tests conducted at the University of Canterbury is shown.

## **2 EXPERIMENTAL TESTING**

Designing an appropriate experimental testing procedure capable of evaluating both the life safety and serviceability limit states for glazing systems is challenging. Not only do the existing seismic testing specifications for façades (NZS4284) require high speed testing, it also requires specific apparatus for water and air penetration testing. To this extent, also note that the current seismic testing protocol for façades (NZS4284) is not mandatory. After consulting with the industry, a few points have been made: 1) the need for high-speed testing is found to be insignificant compared to a standard quasi-static cyclic testing; and 2) water penetration tests are of more interest than air penetration tests. As such, it was decided for this

experimental investigation to utilize quasi-static cyclic testing and water penetration tests (with both cyclic and static air pressure, explained further below).

The experimental set-up (Figures 2-5) consists of two concrete slabs (top and bottom), simulating building floors with a height of 3.6m, which were erected with two pinned steel frames at either end. The structure is fully pinned in the longitudinal direction and is not permitted to move in the orthogonal direction. The rig is connected to a hydraulic actuator which can impose roof displacements of  $\pm 300\text{mm}$  in the longitudinal direction and a force of 800kN. Two additional steel columns are added in the longitudinal direction to simulate floor columns creating an “opening” of 2.976m long by 3.385m high for installing the glazing system. A full-scale glazing system specimen is then installed in the opening which is then sealed on all four sides to ensure realistic building conditions. During the water penetration test, a weather simulator “box” made from timber is attached to the system fully covering the glazing system. An array of sprinkler nozzles 1800mm apart is mounted inside the timber box which is approximately 900mm deep as recommended by NZS4211. Water is then “sprayed” onto the glazing system simulating rain. This system is designed as such that after falling off the face of the glazing, the drained water is reticulated back to the water reservoir (via a pump). Furthermore, to simulate wind, an air blower is utilized to increase the air pressure inside the “box”. The air pressure could then be controlled via a differential pressure sensor and two “air bleeding” valves.



*Figure 2. Experimental set-up for testing of glazing systems in commercial buildings; showing concrete slabs, support frames, timber box and glazing specimen.*



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

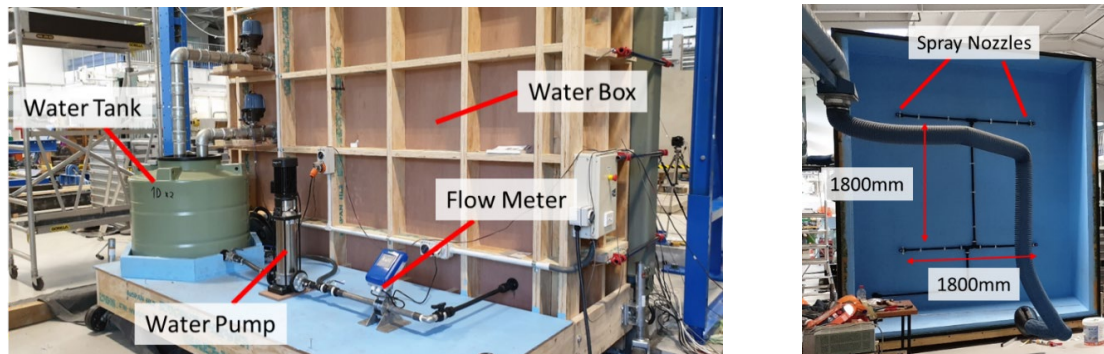


Figure 4. Equipment required for water-tightness test. View from rear (left) and view of spray nozzle locations inside box (right).



Figure 5. Air pressure control unit. Air blower (left), differential pressure sensor (middle) and bleeding valves (right).

The first set of specimens are a common dry glazed curtain wall glazing system with four panes (Figure 6). The two bottom panes had small aspect ratios of 1.426m wide:2.56m tall and the other two top panes had larger aspect ratios of 1.426m wide:0.622m tall. The framing was made from aluminium which provided a glass clearance of 16mm. The aluminium frame is screwed on all four sides to the concrete slab and steel columns. The system is sealed with PVC wedges around all four sides of each glass pane and silicone around all four sides of the aluminium (two sides in contact with concrete, and two in contact with steel).



Figure 6. Glazing Specimen.

The specimen was loaded in-plane following the FEMA 461 loading protocol with a target interstorey drift of 3% achieved in 10 full-cycles (one full cycle involves two positive and two negative demands). After each step, the specimen was also tested for water penetration up until it failed the serviceability limit state (water leakage observed) following the procedure shown in Figure 7.

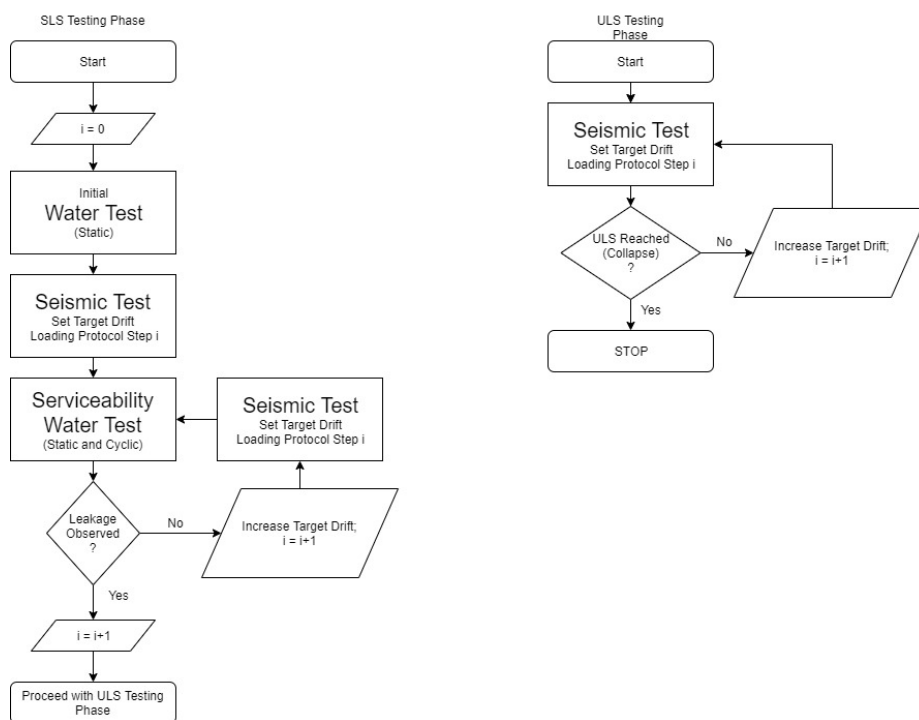


Figure 7. Testing Procedure.

The rig was instrumented with a load cell to measure the force resisted by the actuator, a displacement transducer to measure the roof displacement, particle dots for particle tracking of the glazing system, and potentiometers to collect data on the rigid body movement of the glass pane with respect to the aluminium frame.



Figure 8. Photo showing glazing specimen and instrumentation used in the experimental testing, cameras and red dots used for particle-tracking (left) and potentiometers used to monitor displacements of panes relative to framing (right).

### 3 SEISMIC ASSESSMENT PROVISIONS FOR GLAZING SYSTEMS IN NEW ZEALAND

#### 3.1 The assessment of Secondary Structural and Non-Structural (SSNS) components

The New Zealand Guidelines for The Seismic Assessment of Existing Buildings provides a technical basis for engineers to assess the seismic performance of existing buildings. Section C10 of this guideline presents guidance for engineers conducting a detailed seismic assessment (DSA) of building elements that are not a part of the primary lateral or gravity resisting system. Such elements are referred to as secondary structural and non-structural (SSNS) elements and systems. The primary focus of this guideline is an evaluation of whether or not these elements are expected to represent a significant life safety hazard or have the potential to damage adjacent property. Then, an assessment of these elements and a score is required only if these can pose a life safety hazard.

The earthquake score for an SSNS element is in terms of the deformation capacity of the element and its connections and the deformation demand imposed by the building is to be evaluated by Equation 1:

$$\%NBS = \frac{Q \delta_{capacity}}{\delta_{demand}} \times 100 (\%) \quad (1)$$

where  $\delta_{capacity}$  and  $\delta_{demand}$  are, respectively, the deformation demand and deformation capacity of the element and its connections, and  $Q$  is an element performance factor, equal to 1 for most SSNS elements.

#### 3.2 The Deformation-based assessment of Glazing Curtain Wall framing systems

In the presence of a curtain wall which can represent a life safety risk (falling, shattering, etc.), the New Zealand Guidelines for Seismic Assessment of Existing Building requires a deformation-based assessment, as discussed in section C10.6.8.3 of the guideline. While the inter-story displacement demand can be

evaluated as for any other element of the structural system, according to the provisions reported in section 2 of the same document, the displacement capacity of glazing systems is usually associated with the clearance,  $c$ , between the glass panes and the frames. According to the New Zealand Guidelines the deformation capacity of the generic panel, to include allowance for the glass being seated on setting blocks, is to be calculated with Equation 2:

$$\delta_{panel} = c \left( 2 + \frac{h_g}{b_g} \right) \quad (2)$$

The deformation capacity at inter-story level can then be calculated with Equation 3:

$$\delta_{cap} = \frac{h_{cw}}{h_g} \delta_{panel} \quad (3)$$

According to the guidelines, experimental testing has demonstrated that curtain wall systems are typically able to withstand greater deformations than the initial glass-to-frame contact before glazing falls out. For this reason, the risk of curtain wall failure is adjusted via an element performance factor  $Q$ , which assumes the values reported in Table 1 below.

*Table 1: Performance factor (Q) for different curtain wall types.*

Curtain Wall description	Q factor
Modern commercial curtain wall system	4
Pre-1980 curtain wall or residential curtain wall	2
Frameless glazing or rigid framing	1.25

## 4 RESULTS: THE OBSERVED EXPERIMENTAL RESPONSE AND PREDICTED DEFORMATION CAPACITY

### 4.1 Observed experimental response

Results from three specimens were observed and tabulated in Table 2.

*Table 2: Experimental test result of three specimens*

Specimen	DS1 - Water leakage		DS2 – Gasket failure		DS3 – Glass /Frame Failure	
	Drift (%)	Force (kN)	Drift (%)	Force (kN)	Drift (%)	Force (kN)
1	0.15	1.2	2.1	2.2	4.8	8.4
2	0.7	1.3	3.0	1.4	4.5	7.7
2	0.4	1.8	3.0	2.5	5.7	10.0
Median	0.35	-	2.66	-	4.98	-

Note that three damage states are considered for the tabulation of data, which are; DS1: loss of the water-tightness of glazing units, judged to occur when water first appeared on the inside face of the glazing (Figure 9); 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 (Figure 9); DS3: failure of the frame or glass (either significant cracking or fall-out) (Figure 9).



Figure 9. Damage states 1-water leakage(left), 2-gasket failure(middle) and 3-glass or frame failure(right).

#### 4.2 Predicted deformation capacity (C10)

Considering the geometry of the glass panels tested at the University of Canterbury ( $h_{cw}= 3322\text{mm}$ ,  $h_{g,1}=700\text{mm}$ ,  $h_{g,2}=2622\text{mm}$ ,  $b_{g1}=b_{g2}=b_g=1464\text{ mm}$ ,  $c=16\text{mm}$ ) the deformation capacity of the individual glass panel according to Equation 2 is calculated as:

$$\delta_{panel,1} = c \left( 2 + \frac{h_{g,1}}{b_g} \right) = 2.48c = 39.7\text{mm}$$

$$\delta_{panel,2} = c \left( 2 + \frac{h_{g,2}}{b_g} \right) = 3.79c = 60.6\text{ mm}$$

Hence, the deformation capacity according to Equation 3 at inter-story level is the lower of the two deformation capacities below:

$$\delta_{cap,1} = \frac{h_{cw}}{h_{g,1}} \delta_{panel,1} = 4.75 * 39.7 = 189\text{ mm}$$

$$\delta_{cap,2} = \frac{h_{cw}}{h_{g,2}} \delta_{panel,2} = 1.27 * 60.6 = 77\text{ mm}$$

Calculating the inter-story drift with a deformation capacity of 77 mm is 2.3% drift. Finally, assuming for the glazing system tested a Q factor of 4 (modern commercial glazing system) an estimation of the drift causing the glass fallout is reported below:

$$\delta_{fallout} = Q \delta_{cap} = 4 * 77 = 308\text{ mm} \text{ (9.3\% drift)}$$



As the drift capacity estimated is 9.3% but the observed capacity was 5.0%, it would appear that use of the Q factor of 4.0 (Table 1) is non-conservative and improved guidance should be provided. While the drift values obtained here are very large, the magnitude will of course be a function of the glass-to-frame clearance and concern would exist for glazing with small clearances.

## 5 CONCLUSIONS

This paper has elaborated an experimental testing procedure to evaluate the seismic performance of glazing systems. The experimental procedure can evaluate both the serviceability and life-safety limit states of glazing systems. The paper then proceeds to evaluate the same glazing system configuration from an assessment point of view following the NZSEE/MBIE seismic assessment guidelines section C10. By comparing results obtained, it was found that the assessment guideline was non-conservative in predicting the drift capacity of glazing systems. The experiments show that the glazing systems fail life-safety at 5.0% drift, almost half of the 9.3% drift predicted. The issue is considered to be the Q-factors indicated in the guidelines and some revision of these is recommended.

The experimental testing also revealed issues related to the serviceability performance of glazing systems. For the system tested, it was observed that water-tightness was lost after a median drift demand of only 0.35%. Such damage (relevant to SLS) may cause significant economic losses as the leaks were difficult to observe which may cause further consequential damage, repairs and associated downtime, and as such are of importance. These results show that new guidelines for the serviceability and post-earthquake assessment of glazing damage would be beneficial.

Owing to the large variety of glazing systems used in practice, this research only provides an indication of the seismic capacity of glazing systems. Future work will expand the experimental testing campaign and undertake numerical analyses to increase our understanding of the vulnerability and likely performance of glazing systems in future earthquakes. At the time of preparation of this article further testing is on-going and preliminary results for different glazing systems suggest that improved drift capacities can be achieved.

## ACKNOWLEDGEMENTS

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