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Shake Table Tests of Multiple Non-Structural Elements in a Low – Damage Structural Steel Building

Rajesh P. Dhakal[1], Muhammad Rashid[1], Jitendra Bhatta[1], Timothy J. Sullivan[1], Gregory A. MacRae[1], G. Charles Clifton[2], Liang-Jiu Jia[3] and Ping Xiang[4]

[1] Department of Civil & Natural Resources Engineering, University of Canterbury, New Zealand
rajesh.dhakal@canterbury.ac.nz; muhammad.rashid@pg.canterbury.ac.nz; jitendra.bhatta@pg.canterbury.ac.nz; timothy.sullivan@canterbury.ac.nz; gregory.macrae@canterbury.ac.nz
[2] Department of Civil & Environmental Engineering, The University of Auckland, New Zealand
c.clifton@auckland.ac.nz
[3] Department of Disaster Mitigation for Structures, Tongji University, China
lj_jia@tongji.edu.cn
[4] Department of Structural Engineering, Tongji University, China
p.xiang@tongji.edu.cn

Abstract. The **Ro**bust **Bu**ilding **S**ys**t**ems (ROBUST) project is aimed at enhancing the seismic resilience of buildings by introducing and validating low-damage concepts for the structural and non-structural elements (NSEs). A three-story, full-scale, structural steel building will be tested at the International Joint Research Laboratory of Earthquake Engineering (ILEE) at Tongji University, under uniaxial and biaxial shaking.

This project includes an objective and detailed plan for testing acceleration and drift-sensitive non-structural elements encompassing typical New Zealand design and construction practices along with some low-damage concepts. A total of five NSEs will be included in the test: 1) suspended ceilings, 2) partitions walls, 3) precast cladding panels, 4) glazing, and 5) fire sprinkler piping systems. Partitions walls, being drift-sensitive, will be installed on the first & second floor of the test structure, whereas suspended ceilings and fire sprinkler piping systems, being acceleration-sensitive, will be installed in the upper two floors. Moreover, precast claddings & glazing, which are sensitive to both drift and acceleration demands, will be attached to the upper two floors. Each NSE is currently designed and configured to address specific performance objectives which are essential to improve its seismic performance. The testing will lead to an enhanced understanding of NSEs and provide grounds to improve the existing design standards and practices.

Keywords: Shake Table Test, Non-Structural Elements, Acceleration-Sensitive, Drift-Sensitive.

1. INTRODUCTION

The emergence of performance-based earthquake engineering has led to objective and quantifiable definitions of performance levels for buildings in terms of anticipated financial losses and post-earthquake building functionality. To achieve a certain seismic performance level for a building facility, such as post-earthquake functionality, it is essential that both the structural and NSEs are designed such that their individual performances do no impair the intended performance of that building during or post an earthquake. It has been however observed that the performance of NSEs lags behind the structural system and suffer considerable damage (Dhakal 2010; Dhakal et al. 2011; Filiatrault and Sullivan 2014; Taghavi and Miranda 2003).This results in considerable financial losses and extensive periods of inoperability. From a research perspective, these consequences can be attributed to a limited understanding of NSEs behaviour due to the lack of ample experimental and numerical research as compared to structural elements; this also explains the reason behind the empirical design provisions in the current standards (Egbelakin et al. 2018; Filiatrault and Sullivan 2014). From a practice viewpoint, there is considerable variability in the design and installation approaches for NSEs; the load resisting elements, such as the connections and braces are proprietary in nature lacking a sound engineering design and can vary from building to building. This identifies the need for research work on NSEs, particularly experimental, which can lead to improvement by: 1) quantification of basic response parameters, such as time period and damping, for rational seismic demand estimations; 2) validation of the seismic performance of traditional and novel load resisting mechanisms for different NSEs; and 3) development of validated and simple design provisions for use in design standards.

The **Ro**bust **Bu**ilding **S**ys**t**ems (ROBUST) project is aimed at enhancing the seismic resilience of buildings by introducing and validating low-damage design concepts for the structural and non-structural elements. A three-story, full-scale, structural steel building will be tested at the International Joint Research Laboratory of Earthquake Engineering (ILEE) at Tongji University, under uniaxial and biaxial shaking (Figure 1). The structure has two bays in the longitudinal direction and one bay in the transverse direction, and will incorporate a number of low-damage friction energy dissipaters in the form of sliding hinge joint, resilient slip friction joint, symmetric frication connection and GripNGrab (Chanchi et al. 2013; Clifton 2005; Cook et al. 2018; Hashemi et al. 2016).

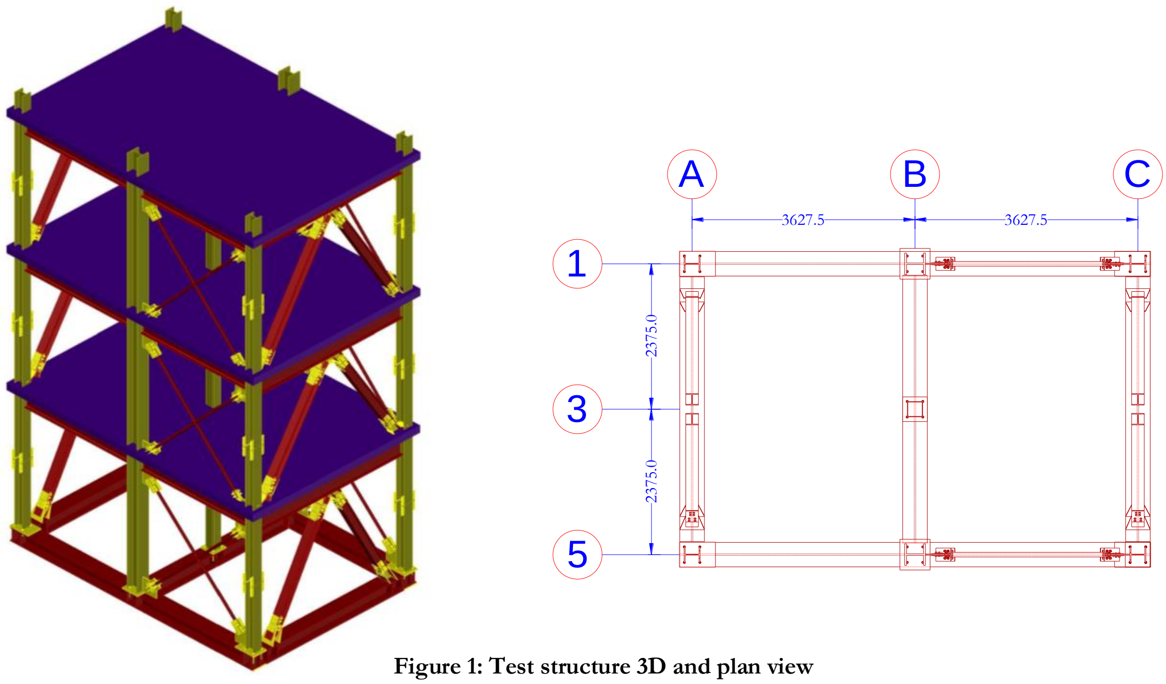


Figure 1: Test structure 3D and plan view

The main objective of testing the NSEs is to investigate and validate the seismic performance of acceleration and drift-sensitive NSEs, encompassing typical and low-damage design concepts, under realistic seismic demands resulting from dynamic interaction with the structural system. A total of five NSEs will be included in the test: 1) suspended ceilings, 2) partitions walls, 3) precast cladding panels, 4) glazing, and 5) fire sprinkler piping systems. Partitions walls, being drift-sensitive, will be installed on the first and second floor of the test structure, whereas suspended ceilings and fire sprinkler systems, being acceleration-sensitive, will be installed in the upper two floors. Moreover, precast claddings & glazing, which are sensitive to both drift and acceleration demands, will be attached to the upper two floors. The design and configuration details of each NSE have been chosen to address specific objectives which are formed by looking into real damage scenarios in past seismic events, survey of existing practices, and opinion from industry experts.

2. NON-STRUCTURAL ELEMENTS

2.1.1 Suspended Ceilings

Damage to suspended ceilings has been widely reported and primarily includes the dislodging and breakage of tiles, failure of the inter-grid and perimeter connections, buckling of the grids, and failure of the perimeter angles (Dhakal 2010; Dhakal et al. 2011; Miranda et al. 2012; Perrone et al. 2018). The perimeter-fixed suspended ceilings are the most widely used suspended ceilings in New Zealand, in which two sides of the ceiling are riveted to the perimeter angles, while the other two sides are floating, i.e. the grid is simply resting on the perimeter angle without any attachment. The primary seismic demand on the ceiling grids is axial force which accumulates along the length of the grid towards the perimeter, where it is to be resisted by a riveted connection with the perimeter angle (Figure 3a). The failure hierarchy for perimeter-fixed suspended ceilings, evaluated from component tests, reveals that the single rivet (3.2mm) perimeter connections are the most vulnerable components of the whole ceiling system (Dhakal et al. 2016). Different solutions have been proposed to avoid the critical damage states, e.g. the seismic clips for inter-grid connections and double rivets for perimeter connections (Dhakal et al. 2016; Pourali 2018; Ryu and Reinhorn 2017).

The use of braced ceiling is becoming popular in NZ for large plenum depths and large floor areas. In such ceilings, the component failure modes discussed above can be avoided as the seismic resistance is entirely provided by the bracing (Figure 2 & 3b). These braces are, however, proprietary in nature and their design details can vary from building to building. The seismic performance of such ceilings, typical of NZ practices, has not been investigated yet.

Recently, a novel low-damage suspended ceiling has been proposed and its concept validated experimentally (Pourali et al. 2017). This ceiling is comparatively simpler to the alternatives discussed above and can avoid the typical damage associated with the grids or the bracing as it is completely isolated from the surrounding structural system and is only hung from the floor slab using hanger wires. These wires have negligible lateral stiffness and therefore are not prone to failure due to seismic loads. Being isolated from the surrounding structure by a gap, the only concern about the fully floating ceiling is it lateral displacement. As demonstrated in Pourali et al. (2017), these displacements can be restrained effectively by filling the perimeter gap with an isolation material.

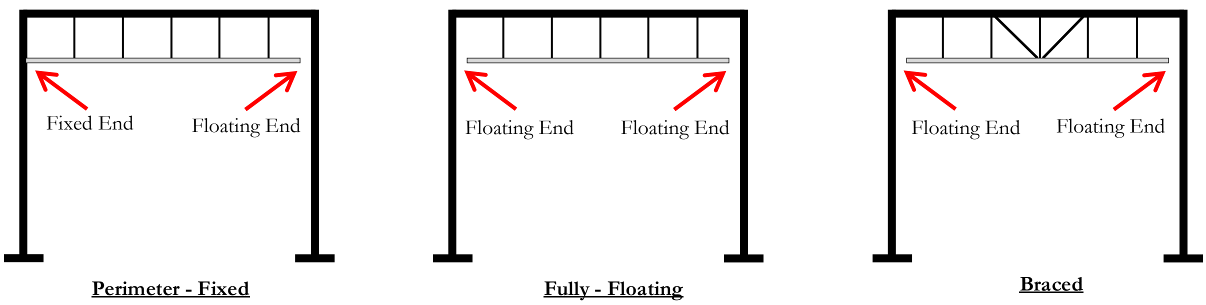


Figure 2: Types of suspended ceilings

a. Perimeter-Fixed

b. Braced

c. Fully-Floating without Isolation Foam

d. Fully-Floating with Isolation Foam

Figure 3: Types of suspended ceilings

The primary objective of this test is to compare the seismic performance of the traditional perimeter-fixed and braced suspended ceilings with the novel low-damage fully-floating variant. The perimeter-fixed and the braced ceiling will each be installed in one half of the second floor in order to compare their performance under the same floor acceleration demands. The fully floating ceiling will be installed on the full third floor to assess its performance, primarily the displacement response and the efficacy of the isolation material in restraining its displacements.

2.1.2 Fire Sprinkler Piping Systems

Damage to fire sprinkler systems is consequential in nature as it can compromise both the fire safety and the functionality of a building during an earthquake. The damage primarily includes fractured piping connections, failure of hangers and braces, and damaged sprinkler heads due to interaction with surrounding building elements, such as ceiling panels (Fleming 1998; Galloway and Ingham 2015; Opus 2017; Soroushian et al. 2014; Tian 2013). Damaged piping connections leads to leakage of water which can flood entire floors and thus, can render a building inoperable (Baker et al. 2012; Galloway and Ingham 2015; Opus 2017; Tian 2013).

Fire sprinkler systems consist of a network of vertical and horizontal supply piping. The horizontal piping has an intricate distribution across a floor and its configuration can vary from floor to floor in the same building (Figure 4). This whole piping network is braced against gravity and seismic load using hanger rods and braces respectively (Figure 4). The braces restrain the pipes from deforming excessively so as to prevent the leakage of connections, and to avoid pounding with the surrounding building elements. The hangers and braces are proprietary systems and connected to the sprinkler pipes and the supporting structure (the beam or slab above) using propriety mechanical connections called attachment components through anchors.

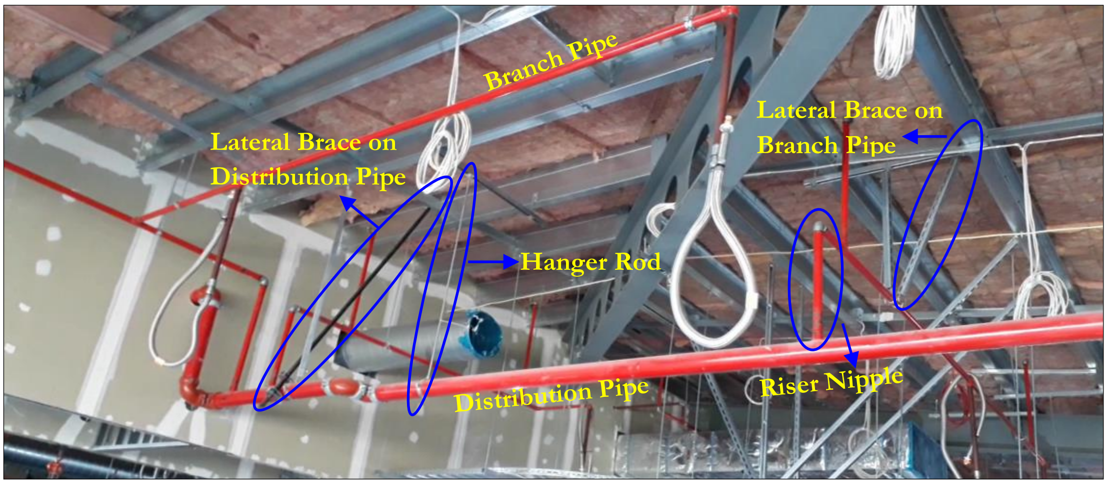


Figure 4: Components of a fire sprinkler piping system

Sprinkler piping systems have been a subject of some extensive experimental and numerical work (Jenkins et al. 2017; Soroushian et al. 2014; Soroushian et al. 2016; Tian 2013). However, given the complexity and random configurations of piping systems, there is still considerable scope to fully understand and characterize their seismic response to formulate simple and validated seismic design provisions. One such required investigation is the displacement demand on long distribution and branch pipes, which is not very extensively studied. The importance of quantifying the displacement demand on long distribution and branch pipes is evident from the shake table test by Soroushian et al. (2016), where a 9.5m distribution pipe displaced almost 50mm at its connection with a branch pipe. This displacement demand is sufficient to cause leakage and almost equals the typical clearance requirements in standards. This observation warrants further investigation into such piping systems.

In this test, fire sprinkler piping systems will be installed on the second and third floor (roof) of the test structure and will only be connected through a riser pipe traversing the floors. The piping configuration will be different on both floors due to the need for different performance aspects to be addressed.

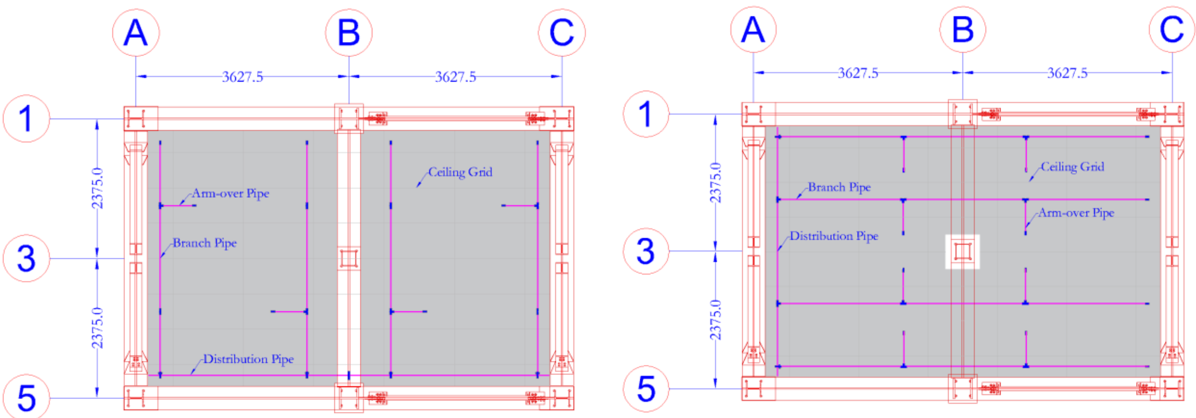


Figure 5: Preliminary sprinkler piping configurations

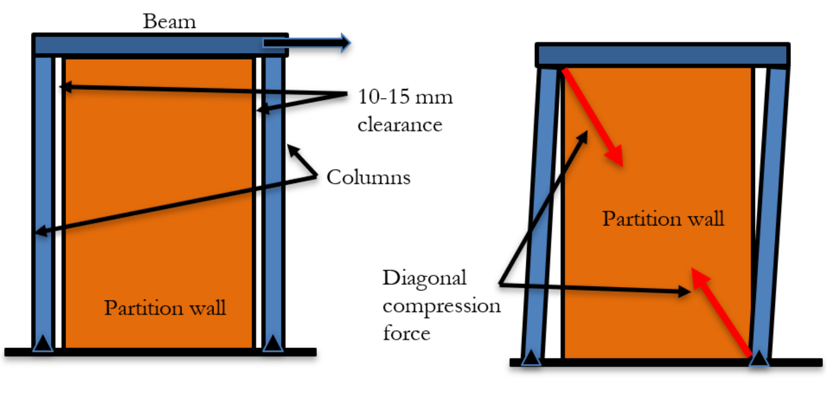
The main objectives for testing the fire sprinkler piping systems are listed below:

1. Investigate the performance of:
    a. Typical brace assembly, which includes the brace element, attachments to the pipe & the building, and the anchor, to investigate its failure hierarchy.
    b. Hanger rods and its anchors.
2. Investigate the displacement demand on long distribution pipes and the riser nipples which branch off the distribution pipes to supply water to the branch pipes.
3. Investigate the displacement demand on long branch pipes and the efficiency of hanger rods (10mm) and steel cables (wires) as bracing in restraining the displacement demands on the branch pipes.

2.1.3 Partition Walls

Partition walls incorporating gypsum wall-boards have been widely used in practice since 1970s because of their fast construction, acoustic control, and attractive appearances. These partition walls are drift sensitive non-structural components which usually have limited deformation capacity leading to damage even at low drift ratios during earthquakes. Early damage to partition walls results in monetary loss corresponding to mandatory repair and consequent downtime of the building. Furthermore, gypsum partition walls can also adversely affect the environment because they must be demolished prior to installing new partition walls. Whitman (1973) reported that repair costs related to partition walls represented around 90% of the total building repair cost after the 1971 San Fernando earthquake. He further suggested that improving the seismic performance of partition walls could be one of the keys to minimizing the losses in buildings during a seismic event. Full-scale experimental tests, which usually comprise of a full-scale drywall partition attached to the structural components (such as floor slabs, frames, walls etc.), are generally preferred over structural analysis since partition wall components cannot be easily simulated. One of the first concepts on 'low damage' detailing on partition walls was put forward by (Lee et al. 2007). They proposed the following detailing configurations:

a) Studs are not to be mechanically connected to the head tracks (or runners) so that they can slip within the tracks as tracks move with the floor or the ceiling, and
b) Clearance of 10 to 15mm to be provided between the intersecting walls or boundary columns.



a) Initial configuration of partition wall **b) Configuration of partition wall after the provided boundary clearance closes**

Figure 6. Intended behaviour of partition wall having clearance at the vertical boundaries

Incorporating these configurations allowed the partition wall to slide without being subjected to significant stresses. Partition walls were damage free until 1.07% drift (~30mm/2800mm) corresponding to the total vertical gap of 30 mm provided between the partition wall and the boundary columns; which was major improvement over partition walls which behaved as "shear-walls". Tasligedik et al. (2015) also proposed similar detailing with some minor variations to reduce the gap width at the intersecting walls or boundary columns by distributing the gaps among the gypsum boards, termed as 'inter-seismic gaps'. Details at the inter-seismic gaps also allowed gypsum boards to move independent to each other. Furthermore, fire-rating on partition walls was ensured by providing strips of gypsum boards around the edges and in the inter-seismic gap of the partition walls. However, bigger gaps are not aesthetically pleasing and require significant amount of gap fillers which indirectly relates to more cost because of additional time labor requirements.

Therefore, 'alternative' detailing for partition walls is being explored at the University of Canterbury to minimize the vertical gaps between the gypsum boards and between partition walls and the boundary elements (for example columns, orthogonal partition walls, etc.). Partition walls having 'L' and 'T' configurations with 'alternative' details will occupy the first and second floors of the test structure (Figure 7). One of the primary objectives for this test would be to investigate the seismic resiliency of this 'alternative' partition wall detailing and its interaction with suspended ceilings on the second floor.

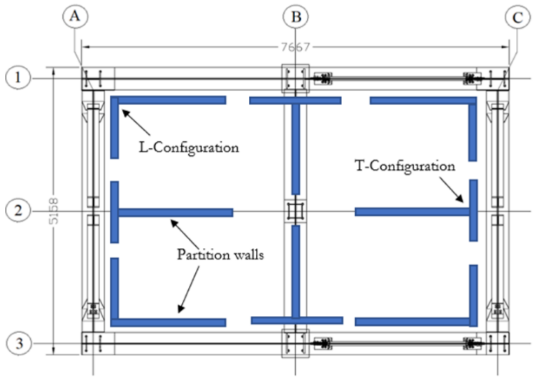
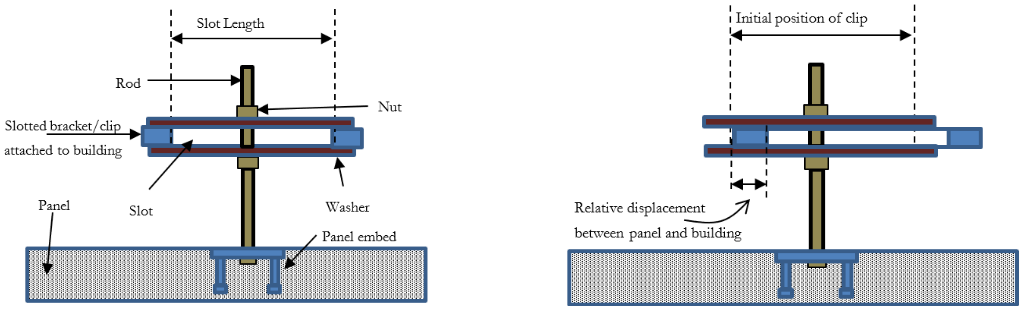


Figure 7. Preliminary configurations of partition walls on first and second floor of the test structure

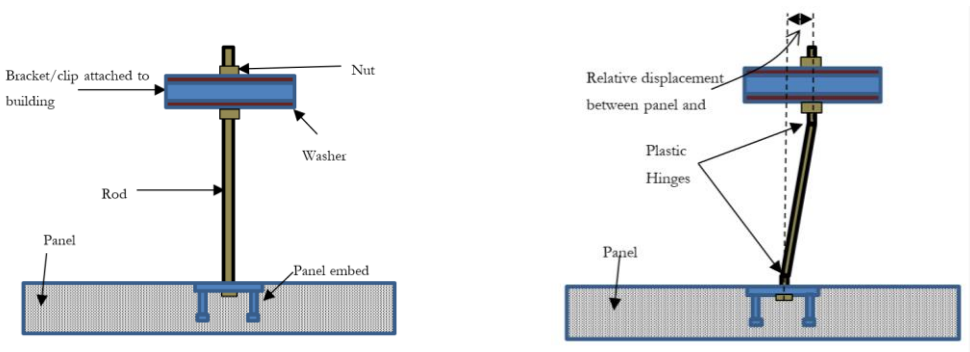
2.1.4 Precast Cladding Panels

The main function of cladding is basically to provide barricade between interior and exterior environment of the building. While doing so, its connections to the structural systems must be able to support the self-weight of the cladding, and distribute the wind pressure applied on the face of the cladding to the main structure. Generally, Precast Cladding Panels (PCPs) are sensitive to both floor accelerations (out-of-plane direction) and inter-story drifts (in-plane direction). Therefore, these panels are designed to satisfactorily resist the out-of-plane forces and accommodate in-plane story drifts. According to (ASCE/SEI 2010), connections to permit movement in the plane of the panel for story drift shall be sliding connections using slotted (sliding connection, Figure 8) or oversize holes, connections that permit movement by bending of steel (flexing connection, Figure 9), or other connections that provide mecahnsisms to accommodate relative movement between the cladding and the supporting structures. Despite these concepts, partial or even complete collapse of PCPs has been observed during recent earthquakes. The damage and collapse of PCPs during the 2009 L'Aquila earthquake and the 2012 Emilia earthquake indicate some shortcomings in the design approaches in panel-to-structure connection details (Bournas et al. 2014; Colombo 2012). During the 2011 Christchurch earthquake, faults in fixings (inability of bolt heads to slide within the horizontal slot of sliding connection because their washers had been welded to the metal angle) led to failure of PCPs. Moreover, the aftershock of 6.3 magnitude (June 13, 2011), following the Christchurch earthquake, resulted in detachment of PCPs and connection damage due to beam elongation. Corner crushing due to clashing between adjacent panels, and rupture of sealing joints due to relative movement between panels, were common damages observed during the 2011 Christchurch earthquake (Baird et al. 2012).



a) Sliding connection details **b) Intended behaviour**

Figure 8. Sliding connection and its intended behaviour during seismic event (Hutchinson 2014)



a) Flexing connection details **b) Intended behaviour**

Figure 9. Flexing connection and its intended behaviour during seismic event (Hutchinson 2014)

It is believed that corner elements are one of the major sources of problems occurring in the precast claddings using sliding slotted connections or flexing connections (Hutchinson 2014). Corner joints are locations where the in-plane panels and out-of-plane panels meet. The in-plane panels tilt rigidly along with the lower slab whereas the out-of-plane panels predominantly move with the upper slab. Therefore, the relative motion encountered by the panels at the corner is the same as the inter-story drift between the floors comprising the panels. Therefore, enough joint gap is provided between panels to avoid panel-to-panel contact and panel-to-structure contact during the maximum displacements of the structure. This consideration resulted in the practice of oversized sealant joints at each corner of the building (Figure 10). This practice is obviously undesirable for architects. As per ASCE/SEI (2010), for a flexible moment frame system the allowable story drift is around $0.02\times h$ to $0.025\times h$, where 'h' is the floor-to-floor height of the building. Generally, for a building with 3.5m floor-floor height, the joint gap turns out to be around 90mm.

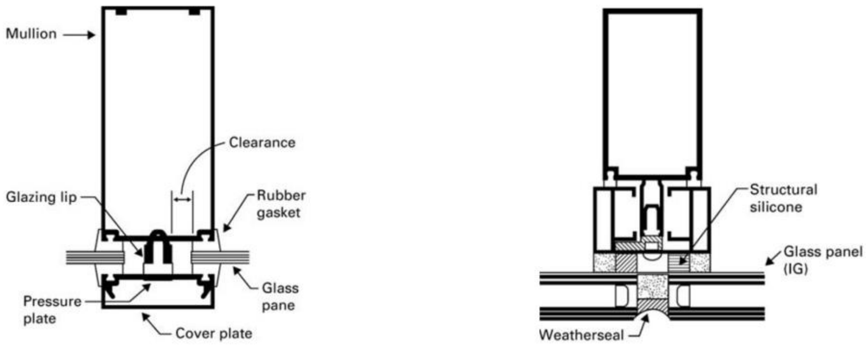
a) Miter joint **b) Butt return joint**

Figure 10. Oversized seismic joints (Hutchinson 2014)

Therefore, one of the primary objectives of this project will be to examine the seismic resiliency of novel connection details (under development at University of Canterbury in collaboration with Lanyon and LeCompte Construction Limited). These new connection details aim to reduce the possibility of clashing between panels located at corners of buildings in addition to minimizing the joint gaps. The precast cladding panels, comprising of these novel connection details, spanning top two floors will be installed at two opposite corners of the test structure (Figure 14 and Figure 15).

2.1.5 Glazed Curtain Walls

Curtain walls with aluminium-frame and in-fill glass, termed as 'glazed curtain walls' (GCW), are typically preferred over many other types of curtain wall systems for multi-story buildings because of their light weight, accessibility to sunlight, ease of construction and aesthetics. The glass panes are kept in place within the frames through some mechanical means. In conventional systems, where external mechanical stops are used to hold the glass pane in place, the space between the stop and the glass is filled with a 'cushioning' material which also forms air and water seal between the glass and the frame. Such material can either be a rubber gasket (in dry-glazed systems, Figure 11a) or a sealant (in wet-glazed systems Figure 11b). Other means to hold the glass in place include the use of adhered silicone sealant which affixes the glass to the frame (in structural silicone glazing (SSG) systems). The aluminium framing is secured to the structural frame (beams or slabs) through clip angles, having required tolerances to account for installation errors and building movements, and restrained from out-of-plane movements. Recently, significant damage to glazing systems has been observed in the 2010 Chile earthquake and the 2011 Christchurch earthquake (Aiello et al. 2018; Baird et al. 2012).



a) Dry-glazed **b) Wet-glazed (structural silicone glazing)**

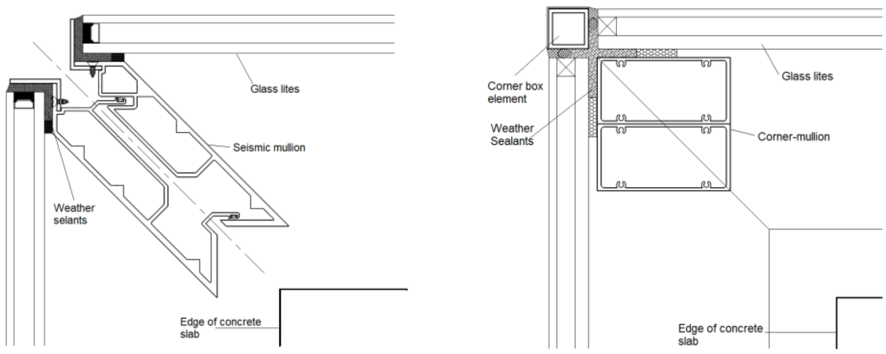
Figure 11. Typical section details for curtain walls (Behr 2009)

a) 2010 Chile Earthquake (Behr 2009) **b) 2011 Christchurch Earthquake (Baird et al. 2012)**

Figure 12. Damage observed to glazing systems in recent earthquakes

These damages often comprised of glass cracking, permanent deformations of the aluminium framing and loss of attachment in structural silicone glazed (SSG) systems. Such damages can pose life-safety hazards as shards of glass were found on the footpaths and streets. Memari et al. (2012) reported that two-sided SSG systems have higher drift capacity than that of dry-glazed systems that use rubber gasket and four-sided SSG systems can have higher cracking drift capacity of about 140% of the dry-glazed system. It can be attributed to the fact that the glass panes do not encounter a framing member as it is isolated from the framing by silicone seals. However, the transfer of lateral loads to the supporting frame depends on inherent properties of silicone, the bond quality between the glass, sealant and the frame. Extreme distortion in the frame can result in reduction of adhesion capacity of the structural sealant under out-of-plane deformations (Memari and Schwartz 2009), and possible detachment of the glass panes. Yet, SSG system have become very popular because of seemingly 'mullion-less' and smooth architectural finishes (Behr 2009).

Prevalent four-sided structural silicone glazed system (4SSG) with two different types of corner details (seismic-mullion, Figure 13a; and corner-box element, Figure 13b), provided by Alutech Doors and Windows limited, will be attached at the corners of the test building which are not occupied by PCPs. They will also span across the top two floors (Figure 14 and Figure 15). This system level test will provide us a platform to better investigate the seismic resiliency of the 4SSG system and compare the performance of the 'seismic-mullion' and 'corner-box' corner details.



a) Seismic Mullion corner configuration **b) Corner-box element corner configuration**

Figure 13. Preliminary corner details for curtain walls

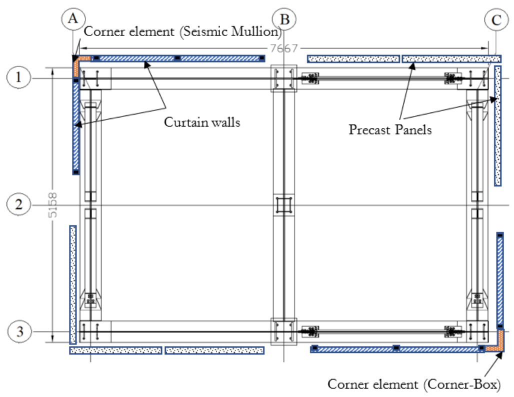
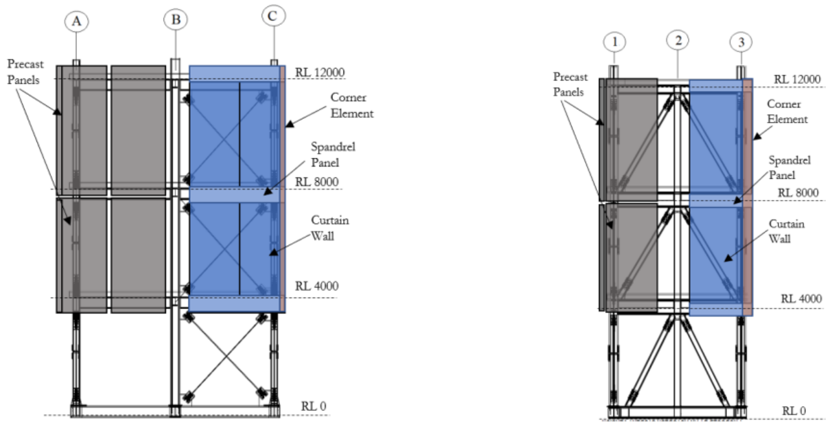


Figure 14. Plan view of precast panels and curtain wall assembly on top two floors of structure



a) Longitudinal Elevation **b) Transverse Elevation**

Figure 15. Elevation view of precast panels and curtain wall assembly

3. CONCLUSIONS

This paper presents an overview of a shake table test of a three-story structural steel building at the International Joint Research Laboratory of Earthquake Engineering (ILEE) at Tongji University. The testing plan includes acceleration and drift-sensitive non-structural elements distributed across the height of the building. The main objective of testing the NSEs is to investigate and validate the seismic performance of acceleration and drift-sensitive NSEs, typical of NZ practices, and encompassing typical and low-damage design concepts, under realistic dynamic loads. This testing will lead to an enhanced understanding of the seismic behaviour of NSEs in New Zealand which is essential to improving the overall performance of buildings subjected to earthquake events.

4. ACKNOWLEDGEMENTS

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