SHAKE TABLE TESTING PLAN FOR MULTIPLE NON-STRUCTURAL ELEMENTS & CONTENTS IN A LOW-DAMAGE STRUCTRUAL STEEL BUILDING

R. P. Dhakal(1), M. Rashid(2), J. Bhatta(2), C. Chen(3), G. Q. Song(3), T. J. Sullivan(1), G. A. Macrae(4), G. C. Clifton(5), P. Xiang(6), L. J. Jia(6)

(1) Professor, University of Canterbury, New Zealand, rajesh.dhakal@canterbury.ac.nz, timothy.sullivan@canterbury.ac.nz
(2) PhD candidate, University of Canterbury, New Zealand, muhammad.rashid@pg.canterbury.ac.nz, jitendra.bhatta@pg.canterbury.ac.nz
(3) Master's student, Tongji University, China, can_chen@tongji.edu.cn, songguanqing@tongji.edu.cn
(4) Associate professor, University of Canterbury, New Zealand, gregory.macrae@canterbury.ac.nz
(5) Associate professor, The University of Auckland, New Zealand, c.clifton@auckland.ac.nz
(6) Associate professor, Tongji University, China, lj_jia@tongji.edu.cn, p.xiang@tongji.edu.cn

Abstract

The Robust Building Systems (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, with multiple structural details, NSEs, and contents under unidirectional and bidirectional horizontal 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 ground level of the test structure, whereas suspended ceilings and fire sprinkler piping systems, being acceleration-sensitive, will be installed in the upper two levels. Moreover, precast claddings & glazing, which are sensitive to both drift and acceleration demands, will be attached to the upper two levels. Further, different contents will be set in the third story to understand their seismic response under different constraints. Each non-structural element is currently designed and configured to address specific performance objectives which are essential to improving its seismic performance. The testing will lead to an enhanced understanding of NSEs and contents, and provide grounds to improve the existing design standards and practices.

Keywords: Shake table tests; structural steel building; non-structural elements; contents; low-damage.

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 structural members and NSEs are designed such that their individual performances do not impair the intended performance of that building during or after an earthquake. It has, however, been observed in recent earthquakes that the performance of NSEs generally lags behind the building structural performance and suffer more damage than the building structure does [13,14,17,39]. 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 the seismic behavior of NSEs, which is 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 [16,17]. From a practice viewpoint, there is considerable variability in the design and installation approaches for NSEs. This identifies the need for research work on NSEs, particularly experimental, which can lead to improvement in understanding and practice by: 1) quantification of basic response parameters, such as vibration 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 Robust Building Systems (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 (Fig. 1). The structure has two bays in the longitudinal direction and one bay in the transverse direction, and will incorporate a number of high-performance connections (low-damage friction energy dissipaters) in the form of sliding hinge joint, resilient slip friction joint, symmetric friction connection and GripNGrab [8,9,11,20]. The test structure will be subjected to unidirectional and bidirectional horizontal shaking with ground motions corresponding to the design-basis (10% in 50 years) and maximum considered earthquake (2% in 50 years) intensity levels for Wellington (soil class C & importance level 2). The set of prospective ground motions will include normal-directivity, near-field forward-directivity (pulse-like), and long duration subduction ground motion records.

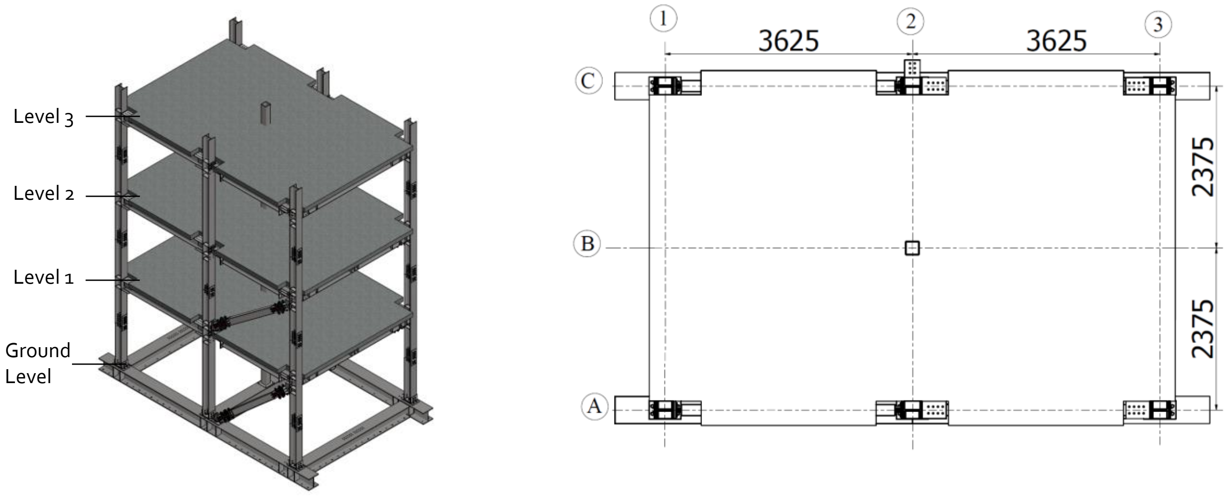


Fig. 1 – Test structure 3D & plan view

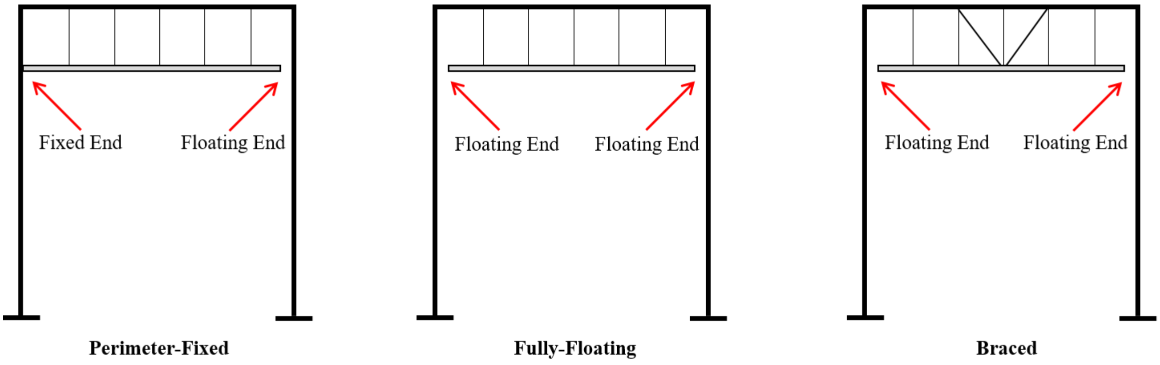
The main objective of testing the NSEs is to investigate and validate the seismic performance of acceleration and drift-sensitive NSEs, encompassing typical and low-damage design concepts, under realistic seismic demands resulting from dynamic interaction with the structural system. A total of five NSEs 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 ground level of the test structure, whereas suspended ceilings and fire sprinkler systems, being acceleration-sensitive, will be installed in the upper two levels. Moreover, precast cladding & glazing, which are sensitive to both drift and acceleration demands, will be attached to the upper two levels. Further, different contents will be set in the third story to understand their seismic response under different constraints. The design and configuration details of each non-structural element 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 feedback from industry experts.

2. Non-Structural Elements

2.1 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 [13,14,25,30]. The perimeter-fixed suspended ceilings are one of the most widely used suspended ceilings in New Zealand, in which two sides of the perimeter 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 (Fig. 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 [15]. 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 [15,31,34].

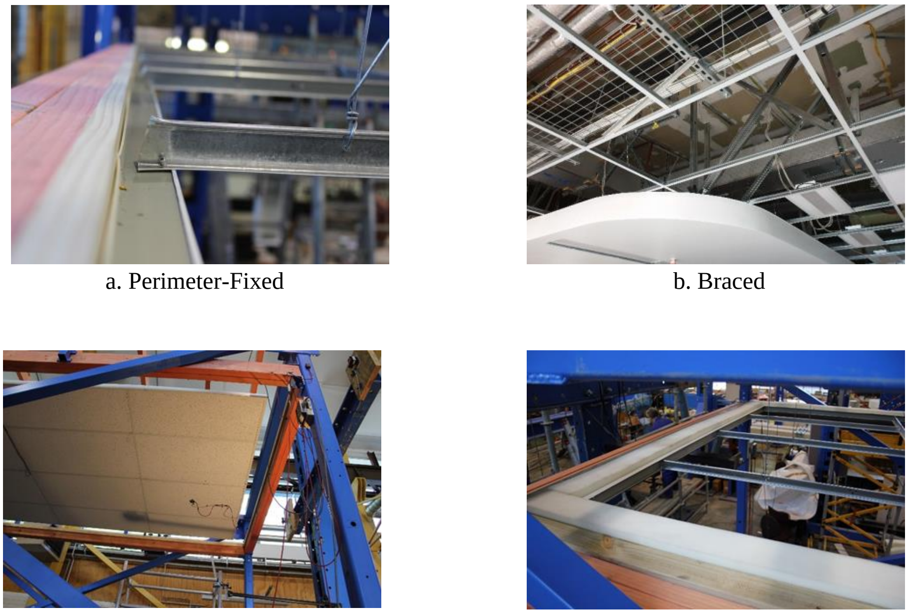
The use of braced ceilings is also popular in New Zealand for large plenum depths and large floor areas. In such ceilings, the component failure modes discussed above can be avoided as the seismic resistance is entirely provided by the bracing (Fig. 2 & 3b). These braces are, however, proprietary in 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.



Perimeter-Fixed **Fully-Floating** **Braced**

Fig. 2 – Types of suspended ceilings

Recently, a novel low-damage suspended ceiling has been proposed and its concept validated experimentally [32]. This ceiling is comparatively simpler to perimeter-fixed and can avoid the typical damage associated with the grids as it is completely isolated from the surrounding structural system and is only hung from the floor slab using hanger wires (Fig. 3c). These wires have negligible lateral stiffness and therefore are not prone to failure due to seismic demand. Being isolated from the surrounding structure by a gap, the only concern about the fully floating ceiling is it lateral displacement. As demonstrated in [32], these displacements can be restrained effectively by filling the perimeter gap with an isolation material (Fig. 3d).



a. Perimeter-Fixed

b. Braced

c. Fully-Floating without Isolation Foam

d. Fully-Floating with Isolation Foam

Fig. 3 – Types of suspended ceilings [31]

The primary objective of this test is to compare the seismic performance of the traditional perimeter-fixed and braced ceilings with the novel low-damage fully-floating variant. The perimeter-fixed and braced variants will each be installed in one half of the second level in order to compare their performance under the same floor acceleration demands (Fig. 4). The fully floating ceiling will be installed on the full third level to assess its performance, primarily the displacement response and the efficacy of the isolation material in restraining its displacements (Fig. 4).

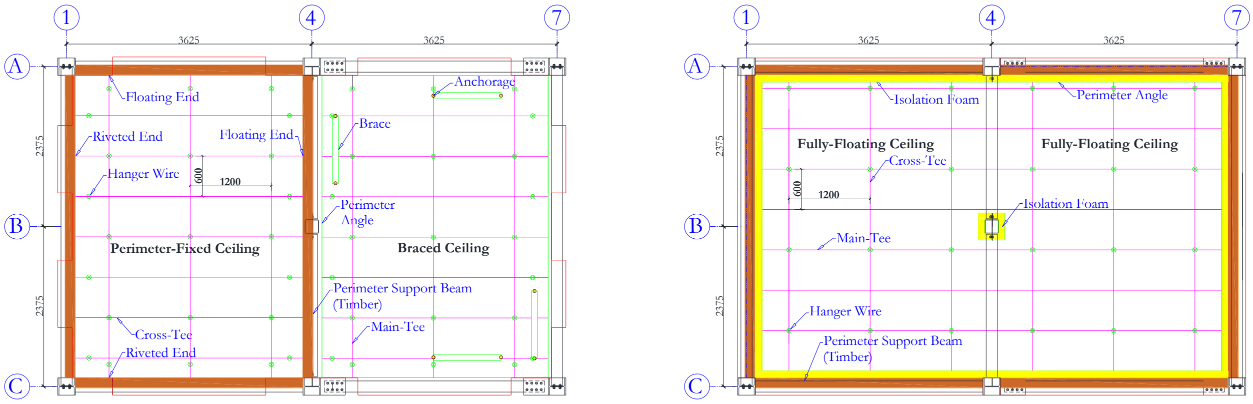


Fig. 4 – Suspended ceilings in test structure

2.2 Fire Sprinkler Piping Systems

Damage to fire sprinkler systems can compromise both the fire safety and 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 [18,19,27,33,37,41]. Damaged piping connections leads to leakage of water which can flood entire floors and thus can render a building inoperable [5,19,27,41].

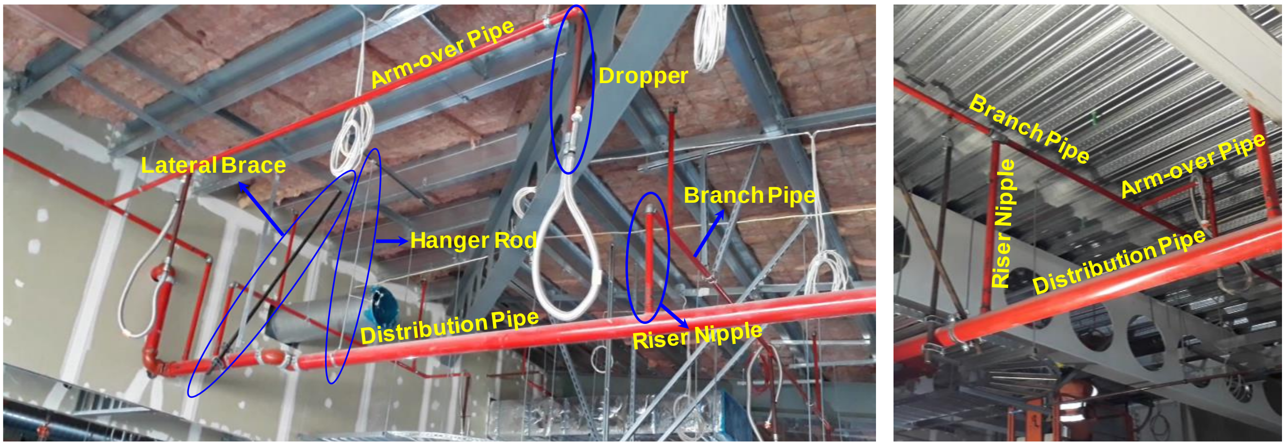


Fig. 5 – Components of a fire sprinkler piping system

Sprinkler piping systems have been a subject of extensive experimental and numerical investigations [21,37,38,41]. However, given the complex piping configurations, and the fact that these systems have not been tested with details typical of New Zealand practices, there is still considerable scope to fully understand and characterize their seismic response to formulate simple and validated seismic design provisions for NZS 4541 [36].

In this test, fire sprinkler piping systems will be installed on the second and third level (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 levels due to the need for different performance aspects to be addressed (Fig. 6).

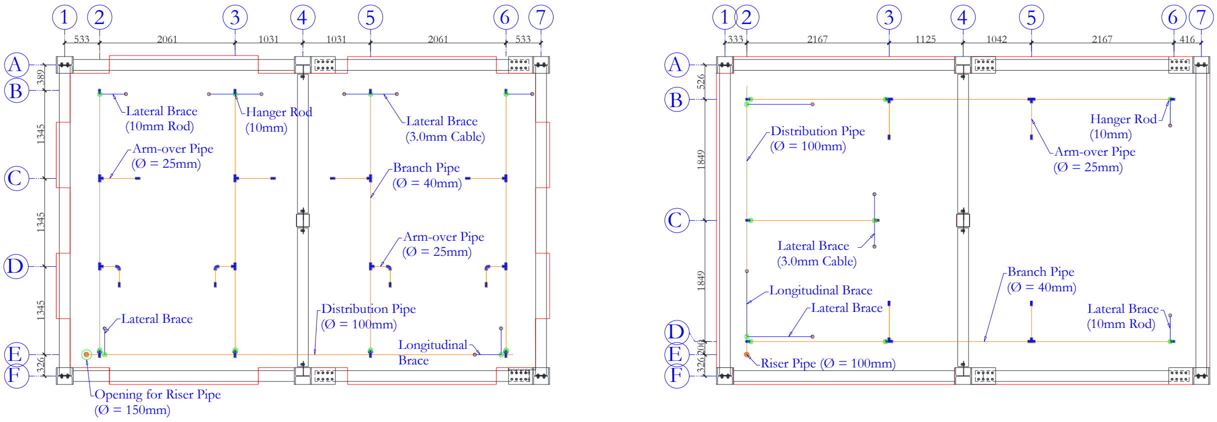


Fig. 6 – Sprinkler piping configurations in test structure

The main objectives for testing the fire sprinkler piping systems are to investigate: i) the performance of a typical brace assembly, which includes the brace element, attachments to the pipe & the building, and the anchor, to investigate the failure hierarchy; ii) the performance of hanger rods and their anchors; iii) the displacement demand on long distribution pipes and the riser nipples which branch off the distribution pipes to supply water to the branch pipes; and iii) the displacement demand on long branch pipes and the efficiency of hanger rods (10mm) and cable bracing in restraining the displacement demands on the branch pipes.

2.3 Partition Walls

Internal partition walls with one or more layers of gypsum wallboards mechanically attached to the light steel stud or wood frame using screws or nails are common in New Zealand, Unites States and some

European countries. They provide a sound and fire proof space in residential and commercial buildings. However, due to brittle finish materials such as drywall, plaster and stucco these walls show limited deformation capacity leading to damages at 0.2% inter-story drift and total loss of economic value around 2% inter-story drift [24]. The damages to internal drywall partitions have been extensive following the 2010 Darfield earthquake [13], 2011 Christchurch earthquakes [40] and 2016 Kaikoura Earthquake [3]. Some examples of the damages are shown in Fig. 7. Such widespread damage can lead to evacuation, consequent downtime and repair costs, which can reach up to 90% of the total building repair costs [12,42]. It is, therefore, crucial to increase the seismic resilience of partition walls to avoid such unfavorable outcomes. Several tests of partition walls with isolated (not mechanically attached) steel studs and tracks/runners, vertical joint gaps at the interfaces of wallboards and between the wallboards and adjacent vertical boundary elements (e.g. structural column, orthogonal partition wall) have shown improved seismic performance of the partition walls [22,28,40]. However, larger widths of vertical gaps cause aesthetic issues and higher initial costs associated with gap fillers and labor requirements.

Fig. 7 – Damaged partition walls [3,13,40]

Considering the above, novel detailing for partition walls is being explored at the University of Canterbury to increase the seismic resilience of the partition walls with minimum vertical gaps between the adjacent gypsum boards and between partition walls and the boundary elements. The novel details allow the partition walls to rock to up to the design drift without any diagonal compressive forces being developed.

In order to observe and verify the seismic resiliency of the partition walls incorporating these novel details, three configurations of the partition walls (‘Planar’, ‘L’ and ‘T’) with these novel details will be placed in the ground level of the test structure. The ‘Planar’ configuration will be attached on top of the ring beam and the top beam directly above, whereas, the ‘L’ and ‘T’ configurations will be attached directly on top of the shake table below and the composite deck above as shown in Fig. 8.

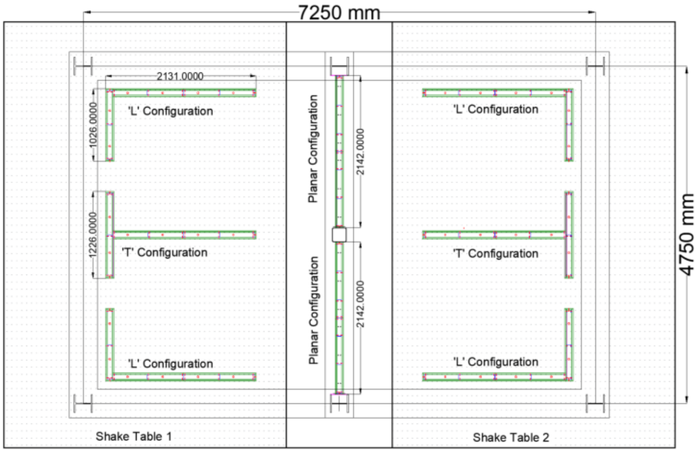


Fig. 8 – Partition walls in test structure

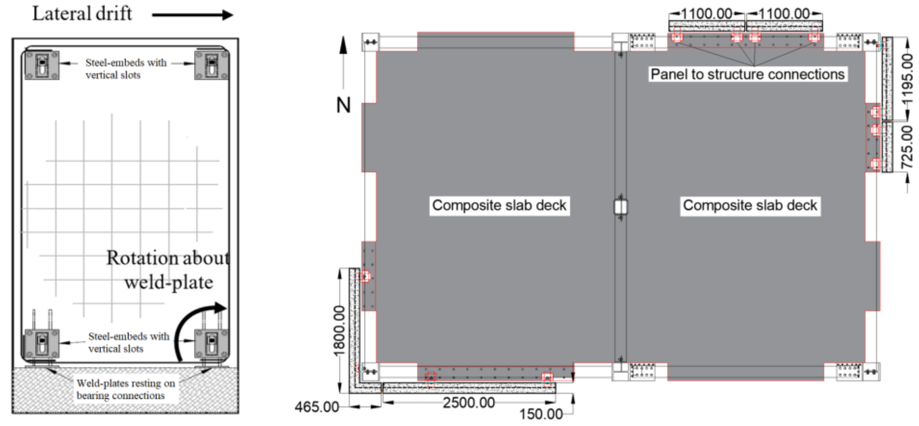
2.4 Precast Cladding Panels

Architectural cladding or façade systems came into picture with the advent of frame structures. The main function of cladding is to provide a barrier between the interior and exterior environment of the building. In seismically active zones, precast concrete panel systems are generally characterized by their connections and joints. It is common practice to isolate the precast cladding panels from movements of the flexible structure through tie-back (slotted/oversized holes) or push-pull (flexible threaded rods) connections [1,29]. Unfortunately, several failures of sliding fastenings (and/or panels) were observed following the recent earthquakes around the world [2,4,10,23] due to faulty installation and/or inadequate displacement and strength capacities of the connections (Fig. 9). The slotted connections typically performed poorly in relation to their design intent during the recent Canterbury earthquakes [35]. Damages to the precast cladding panels can lead to economic losses, repair downtime and fatalities. This has motivated the development of novel precast concrete cladding connections which allow panels to rock under seismic actions, without any significant diagonal forces being developed within the panels, to increase the seismic resiliency of the panel system.

Fig. 9 – Damaged panels [2,10]

The low-damage connections to be used in this research include steel-embed with vertical slots and weld-plates cast into the panels as shown in Fig. 10a. The weld-plates seat on top of the bearing connections and prevent the local spalling and chipping of concrete during rocking of panels. The vertical slots in steel embeds allow panel to efficiently rock up to desired inter-story drift while resisting the out-of-plane face loads in the panels. They are also expected to reduce the possibility of clashing between panels located at corners of buildings even at small vertical joint gaps. Further details regarding the concept, design, fabrication, installation and higher seismic resiliency of the panel system under lateral cyclic loadings can be found in [6,7].

To verify the improved seismic performance of the precast panel system comprising these novel connections under dynamic shaking, one story height precast cladding panels will be installed at the diagonal corners on the upper two stories of the test structure as shown in Fig. 10b.



a. b.

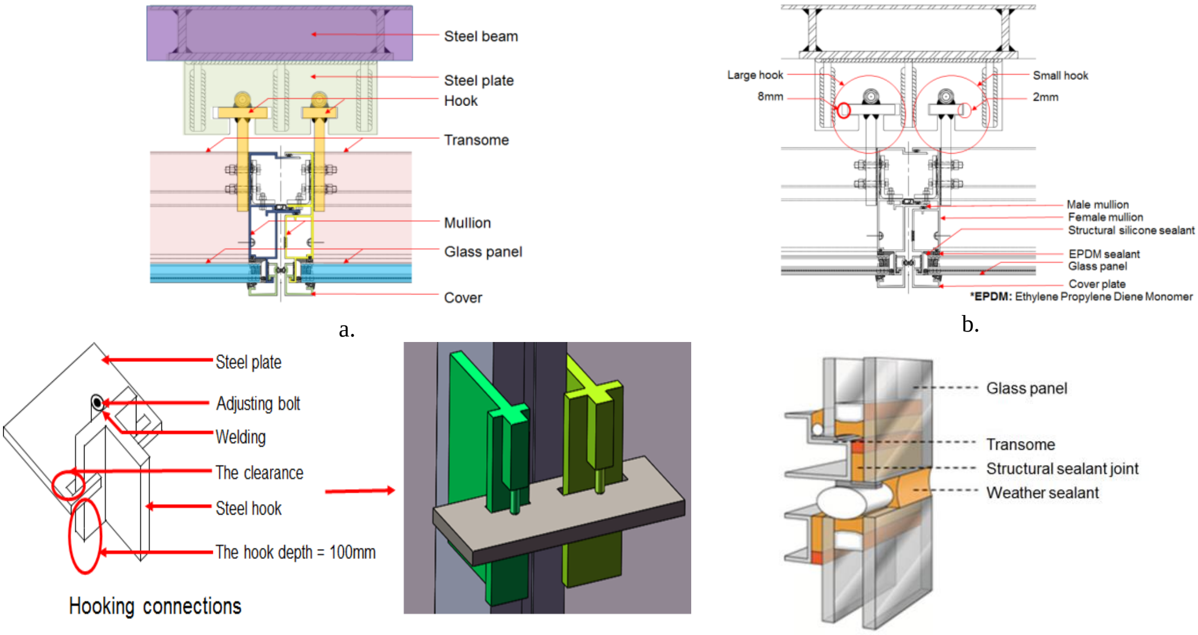
Fig. 10 – a) Novel steel connections; b) Plan showing panel configurations at two opposite corners of the test structure.

2.5 Glazed Curtain Walls

Unitized glazed curtain walls (UGCWs) have become widely used as exterior cladding of multistory building structures. They are regarded as desirable because of their aesthetic, thermal, lighting and construction characteristics. However, damage in previous earthquake events, as shown in Fig. 11, has caused significant economic loss and posed a life-threat to passersby and to occupants.

Fig. 11 – Glazed Curtain Wall Damages [4,43]

UGCWs typically consist of pre-assembled modular panels consisting of several panels of glass held within metal (often aluminum) frames with vertical elements (mullions) and horizontal elements (transoms) by structural silicone sealants. Soft material is also placed between panels to provide protection of the building from the external environment. It may be seen that there are 3 barriers to air movement (with 2 internal chambers). The glass, frame, and soft material (silicone or rubber), together provide lateral force resistance (Fig. 12). In typical Chinese construction, panels are suspended from the top by hooks (which allow uplift), and sit within slots on the top of the panels below which allow in-plane movement and vertical uplift, but limit out-of-plane movement. Panels are then clipped together along the vertical edges. In some cases, especially when large inter-story drifts are expected, shear keys are placed at the bottom of panels into the top of the panel below restricting in-plane movement.



a. b. c. d.

Fig. 12 – (a) Plan view of mullion; (b) Sealant details; (c) Hook details; (d) 3D view of transom [26]

UGCWs are to be placed on the top two levels and opposite corners of the test structure. The UGCWs configuration includes three side-by-side primary panels in the longitudinal direction and two adjacent panels in the transverse direction at each corner as shown in Fig. 13. UGCWs panels at one corner are equipped with shear keys, while no shear keys are provided at the other corner.

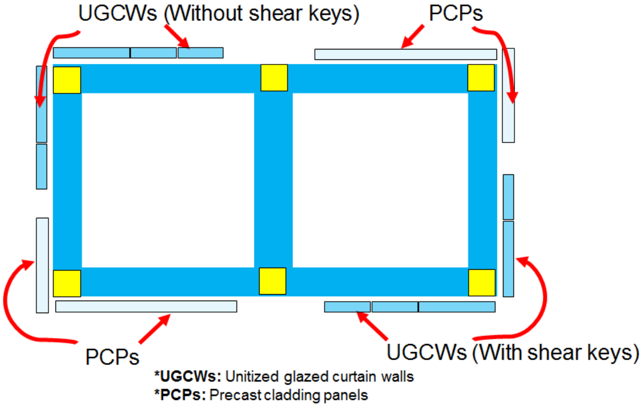
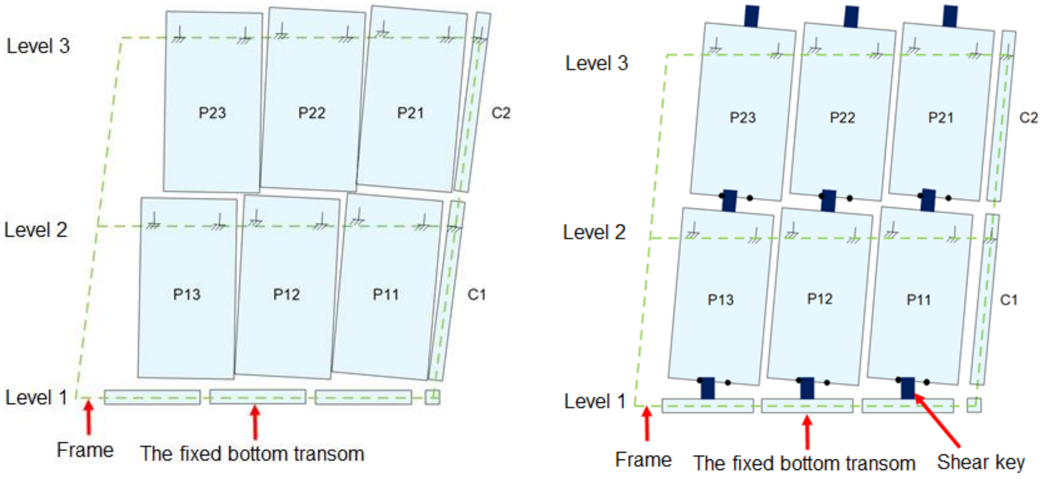


Fig. 13 – UGCW Test Configuration

The expected effect of shear keys on deformation mode is shown in Fig. 14. It is expected that large drifts with minimal damage may be obtained with shear keys, but even when shear keys are not provided the performance may also be satisfactory for some configurations and when inter-story drifts which are not too large. For UGCWs without shear keys, the drift capacity may be related to the clearance between adjacent panels.



a.

b.

Fig. 14 – Deformation mode of UGCWs: (a) without shear keys; (b) with shear keys.

2.6 Contents

During recent severe earthquakes, it was observed that contents, such as beds, bookshelves, tables and photocopiers might move over long distances at high velocity and cause injuries, damage, and business disruptions. A number of analytical and experimental studies have been carried out on the sliding of contents at the University of Canterbury [44]. For further study of the seismic response of contents under different constraints, five groups of contents will be set in the third story. The five groups of contents are shown in Fig. 15. The different layouts are introduced as following:

i. A table obstructed by the partition wall (one-way sliding), a computer on the table and a chair;

ii. A table not obstructed by the partition wall (two-way sliding), a computer on the table, a chair and a manikin;
iii. A table restrained to the partition wall (no sliding), and a computer on the table beside the partition wall;
iv. A table restrained to the partition wall (no sliding), and a restrained computer on the table;
v. Two bookshelves, with one obstructed by the partition wall (one-way sliding), while the other one is restrained to the partition wall (no sliding).

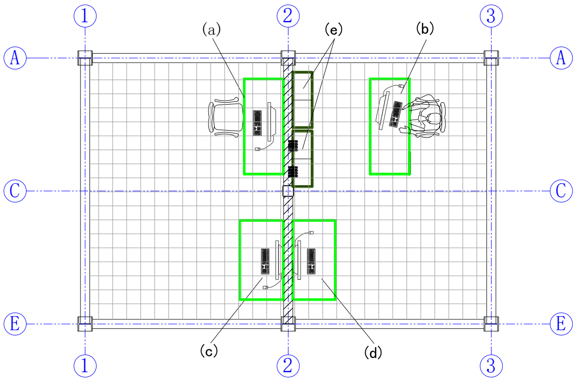


Fig. 15 – Plan view of contents set in the third story

The effectiveness of reducing damage by putting braces, cushions or other devices between contents and the floor or the wall will also be tested. Cameras will be placed around the room and grids will be drawn on the floor, so that the behavior of contents during earthquakes can be observed and their displacements can be measured indirectly. The test results will be used to examine the accuracy of the prediction equations given in [44]. Through this test, we will have a deeper understanding of the seismic response of contents and find remedies to reduce the damage caused by the movement of contents.

4. Conclusions

This paper presents an overview of plans for a shake table test of a three-story 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 and contents distributed across the height of the steel framed 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. Further, different contents will be set in the third story to understand their seismic response under different constraints. This testing will lead to an enhanced understanding of the seismic behavior of NSEs and contents in New Zealand and China, which is essential to improving the overall performance of buildings subjected to earthquake events.

5. Acknowledgements

This work described is part of a joint NZ-China research programme with the International Laboratories on Earthquake Engineering (ILEE), Tongji University, Shanghai, China and directly with Tongji University, Shanghai, China. Direct NZ funding is kindly provided by the Building Research Association of NZ (BRANZ) under the Building Research Levy, the Earthquake Commission (EQC), the HERA Foundation (a charitable trust associated with HERA), QuakeCentre, the Tertiary Education Commission funded QuakeCoRE (the NZ ILEE partner through whom the NZ funding is also coordinated), and the University of Auckland (UA). Donations of materials is kindly provided by Comflor, Hilti Corporation, Forman Building Systems, Gripple, Lanyon & LeCompte Construction Ltd., and Alutech Doors & Windows Ltd. Expertise has been generously provided by a number of NZ industry representatives. The authors gratefully acknowledge this support. Opinions expressed are those of the authors alone. The QuakeCoRE paper number is 0528.

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