Application of resilient rocking cores in low damage mass timber structures: A case study

A. Hashemi, P. Quenneville
The University of Auckland, New Zealand

H. Mpidi Bita, R. Malczyk
Timber Engineering Inc., Canada.

S. Varier
Pryda ITW New Zealand Ltd., New Zealand.

P. Zarnani
Auckland University of Technology

ABSTRACT

The application of mass timber structures made with massive wooden panels such as Cross Laminated Timber (CLT) has significantly increased in the last few years owing to their architectural and structural advantages, as well as their relatively lower carbon footprint compared to other materials. Although many mass timber structures have been constructed in non-seismic regions worldwide, the uptake is relatively lower for seismically active areas. This can be mainly related to the lack of knowledge and reliable seismic resisting concepts for such structures. To address this issue and to improve the uptake, researchers and engineers have been working on developing and implementing new concepts for seismic resistant mass timber systems.

This paper presents a novel case study structure, the oN5 building, made with mass timber elements and located in British Columbia, Canada. The main lateral load resisting system was comprised of a rocking CLT core equipped with resilient connections used as hold-downs. The connectors were designed and tested in New Zealand before being shipped and installed on-site. Given that the New Zealand or Canadian standards do not cover such structures, the building is designed based on FEMA guidelines and fundamental engineering principles. The design approach, construction process and lessons learned from the project are presented and discussed. The findings help engineers and

researchers better understand the behaviour of low damage mass timber structures and make them able to perform efficient and optimised designs for such structural systems.

1 INTRODUCTION

The application of mass timber elements such as Cross Laminated Timber (CLT) has been gaining publicity in the last decade given the global pressure to have more green and sustainable structures and infrastructures (Karacabeyli et al. 2013). Nevertheless, their application in active seismic regions (such as most of New Zealand and the west coast of North America) has always been challenging. Previous experimental studies showed that despite the acceptable seismic performance of such structures (Ceccotti et al. 2013), their performance against repeated cycles of loading and unloading (e.g. multiple events and/or aftershocks) could be questionable (Yasumura et al. 2015). Furthermore, supplemental energy dissipation machinimas may need to be considered to control the response accelerations (Popovski and Gavric 2015). Wood is a brittle material by nature; thus, the required ductility and energy dissipation for earthquake performance comes from the type and behaviour of the connections. Therefore, several attempts have been made to address these issues and develop more resilient mass timber structural systems.

This paper presents a case study where a connections solution that was developed at the University of Auckland, New Zealand, is used for the resilient seismic design of a mass timber project in Vancouver, Canada. In terms of seismicity, Vancouver stands between Christchurch and Wellington in New Zealand, so it has relatively demanding seismic requirements. Such buildings are not covered by current guidelines or standards, so the design was done using first principles and common engineering solutions. This paper provides an insight for researchers and engineers about how to design and analyse mass timber buildings with resilient connections.

2 THE CASE STUDY PROJECT

Named for its location near the intersection on Ontario Street and East 5th Avenue in Vancouver, Canada, oN5 is an innovative four-storey building designed and constructed to showcase the potential for commercial mass timber. The four-storey building, 840 m2, designed by Hemsworth Architecture and Timber Engineering Inc. (formerly Equilibrium consulting Inc.), is scheduled to be completed in 2022. Figure 1 shows photos of the building during construction. The building is the new home for Timber Engineering Inc., an engineering firm with a worldwide reputation for its advanced timber engineering expertise.

Figure 1: The oN5 Building during construction (Credit KK Law Courtesy – Naturallywood.com)

Figure 2 illustrates half of the building plan (left) and section (right). In plan, the building is approximately 7.6 m wide and 36 m long. In elevation, the roof level is at 17 m, approximately. The gravity load-resisting system (GLRS) of the top three levels (including roof) consists of cross-laminated timber (CLT) floor/roof panels supported on CLT core and walls in both directions. Both roof and floor panels were 5ply (175mm) whereas the core has 7-ply (245mm) and 5-ply (175mm) running in the short and long directions, respectively. All CLT panels have equal layer thickness (35mm) and are E1 grade with Spruce-Pine-Fir 2100Fb-1.8E.

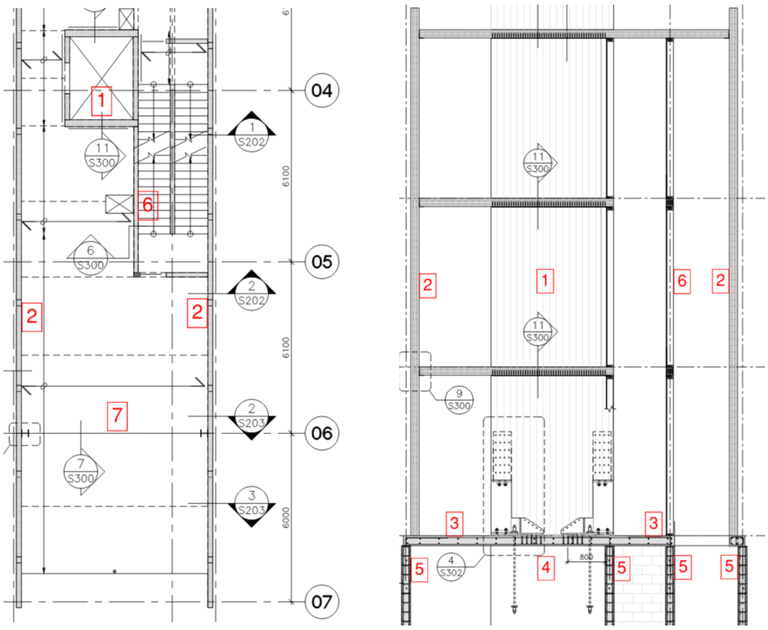


Figure 2: Half of the building plan (left); and Building section (right)

The external walls (Figure 2) were also 5-ply panels (175mm) running in the long direction of the building. The three-storey mass timber portion rests on a 225 mm concrete transfer slab. The CLT core lines up with 250/300 mm concrete core below the transfer slab. The 5-ply 190 mm reinforced masonry walls (see 5 in Figure 2) are directly underneath the external 5-ply CLT, running in the long direction. The walls around the stairs (see 6 in Figure 2) are wood framing (13mm ply on 38×140 studs) at the mass timber portion and reinforced masonry below podium level.

The CLT floor and roof panels act as a diaphragm which transfers the seismic and lateral wind loads to the CLT core and walls at the mass timber portion. Below the transfer slab, the lateral load resisting system is composed of a concrete core (lined-up with the CLT core) and a reinforced masonry wall (lined up with the CLT walls in the long direction). As shown in the plan, the CLT diaphragm cantilevers in the short direction by approximately 15 m on either side of the core. In order to control the lateral deflection of the diaphragm in that direction, steel moment frames (see 7 in Figure 1 2) are added at every level at both ends of the building in plan.

As a demonstration building project, oN5 uses innovative solutions which contribute to the advancement of the emerging mass timber construction, with respect to resiliency, fire, acoustic, vibration, and disproportionate collapse prevention performances, as well as energy efficiency, assembly, and installation. This paper presents the unique structural features implemented to address the structural challenges associated to the design and construction with respect to the seismic performance of the building.

3 STRUCTURAL SOLUTIONS

3.1 Hybrid building

With a width of only 7.6m, oN5 (see Figure 3) called for a creative structural system where all structural elements were proportioned to meet not only the architectural and structural requirements but also construction and building physics constraints. The considered hybrid structural system optimised the application of the individual structural material: i.e., mass timber on masonry and concrete podium construction. The reinforced masonry long walls enabled for construction along the property line without disturbing neighbouring buildings.

Figure 3: Zero-lot-line (Credit KK Law Courtesy – Naturallywood.com)

Using in-situ concrete for both the transfer slab and the core below the podium allowed for simple and direct transfer of the high gravity and lateral forces from the CLT core above while maintaining reasonable wall thickness. Having a podium also enabled to start of mass timber construction at an elevation higher than neighbouring buildings (5.9m above grade), which permitted the use of cranes for lifting and installing mass timber above. The lightweight wood enabled the use of a regular (not oversized) crane for the installation of three-storey tall prefabricated CLT roof/floors and wall panels (see Figure 2).

3.2 Podium construction

To optimise the seismic performance of the top three-storey mass timber portion, a two-stage analysis approach as per the National Building Code of Canada (Tremblay et al. 2015) was followed. The high stiffness of the reinforced masonry walls and concrete core, relative to the CLT system, enables to obtain a rigid box at the platform level. Using a two-staged approach, where $k_{lower}>3\times k_{upper}$, oN5 building was analysed as two separate structures. Herein, k_{upper} is the stiffness of the upper portion, and k_{lower} is the stiffness of the lower portion of the building, below the transfer slab. The design of the lower portion included the addition of the forces generated by applying the lateral capacity of the upper portion.

Based on the capacity design approach, the lateral design of the upper mass timber portion was designed using $R_d\times R_o$ (ductility and overstrength factors) equivalent to the considered CLT shearwall system, whereas the lower stiffer portion would be designed elastic using $R_d\times R_o=1.3$. Figure 4 shows the general arrangement of the numerical models developed for the seismic analysis.

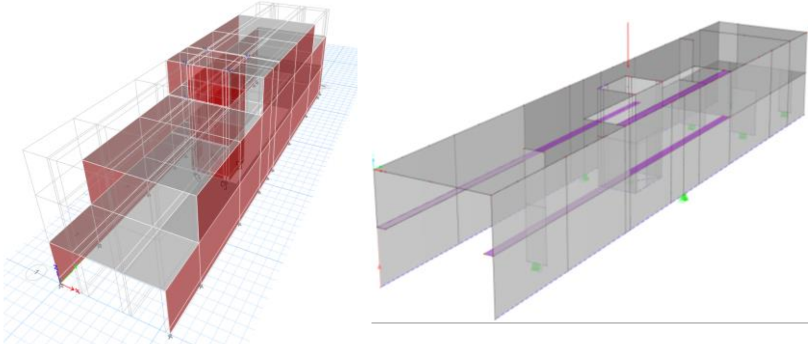


Figure 4: Numerical model of the mass timber upper portion – left; and RFEM model of the lower concrete/masonry portion – right

3.3 CLT Diaphragms

Like the diaphragm analysis, CLT shearwalls analysis and designs are governed by the connections, assuming that the panels themselves mostly as rigid bodies and analysed using suitable mechanics. The 2019 Canadian standard (Tannert 2019) recommends that CLT shearwalls act in rocking or in a combination of rocking and sliding. For the oN5 building, all CLT wall panels are balloon-type, continuous from the concrete transfer slab to the roof, with the floor panels connected to their sides. Typical three-storey and two-storeys CLT wall panels are approximately 11mx3.0m and 8.7mx3.0, resulting in aspect ratios of 3.6 and 2.9, respectively. These aspect ratios ensured the ductility of the building through the desirable rocking mechanism of the CLT panels when subjected to lateral loads. The CLT core is composed of a single panel, with rocking shown in Figure 5 as the kinematic mode. The behaviour of the CLT walls in the long direction is governed by coupled-panel kinematic behaviour, where the panel-to-panel joints allow each panel to rotate about its respective point of rotation, as shown in Figure 5 right.

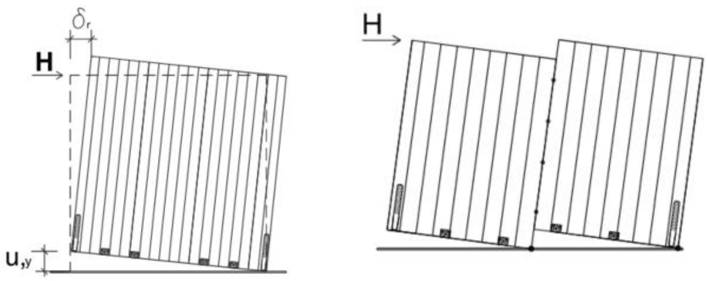


Figure 5: Displacement mechanism

For CLT panel in balloon-type, the components contributing to the lateral deflections due to horizontal forces are: i) bending of the panel; b) shear of the panel; c) rotation of the panel; d) sliding of the panel; and e) slip of existing panel-to-panel joints. Given the aforementioned zero-lot-line site constraints, the design limits the total drift of the building to approximately 2.0% drift, with 1.5% considered as the design target for ultimate limit state design. The oN5 building uses innovative hold-down components, the Resilient Slip Friction Joint (RSFJ) developed at the University of Auckland to reduce the total lateral drift of the building while meeting the target ductility by ensuring that rotation (rocking) of the walls governed with other deformations deemed negligible. The inherent self-centring characteristic of these devices ensured the global re-centring behaviour of the core and the buildings. This concept has been successfully tested for rocking CLT (Hashemi et al. 2017) and LVL (Hashemi et al. 2020) walls.

As shown in Figure 6, four (4) RSFJ were installed at every corner of the CLT central core as the main seismic LLRS providing ductility in both orthogonal directions. Hold-downs were not used for the long CLT walls, assuming energy dissipation is provided through the panel-to-panel joints.

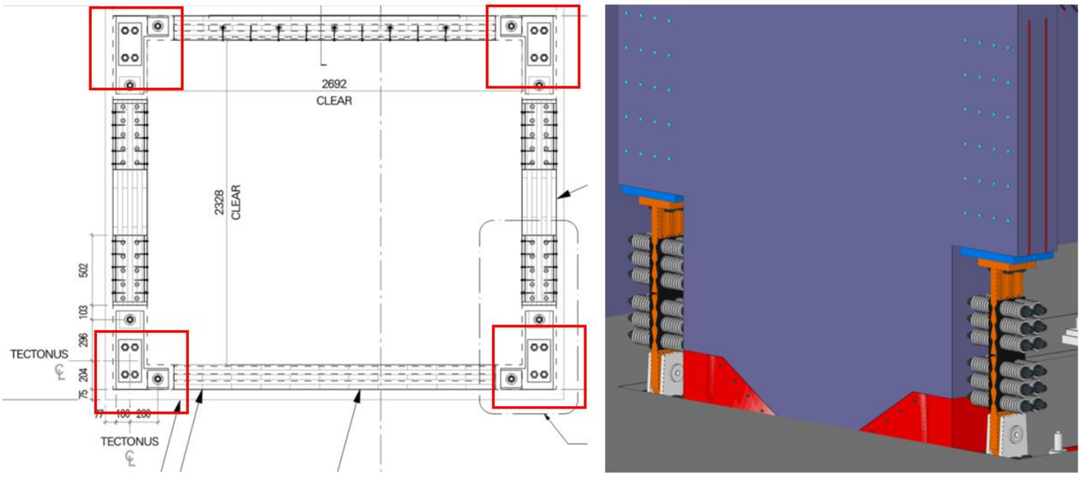


Figure 6: Location of RSFJ hold-down plan view (left), and isometric view of single panel (right)

4 PERFROMANCE-BASED SEISMIC DESIGN AND ANALYSIS

This building is designed for a design life of 50 years with an importance factor of 1.0 (normal occupancy). The 3-storey mass timber building has a footprint of 34.1 m by 8.2 m an inter-storey height of 3.6m, and top storey of 3m. As mentioned, the lateral load resisting system in one direction is fixed base CLT walls and in the other direction is a rocking CLT core. The maximum allowable drift for the building is 1.5% for the rocking direction to target a low damage performance. The building is in Vancouver, and the soil type is classified as Type C. The following sections will describe the method used and details of the analysis.

The lateral elastic forces are calculated as per the NBCC cl.4.1.8.11 using the lateral force method. The parameters for site-specific seismic hazard spectra for a 5% damped horizontal acceleration of 0.2, 0.5, 1.0, 2.0, 5.0 and 10.0 sec periods, with PGA and PGV for a 2% probability of exceeding in 50 years were taken from Table C-3 of NBCC2015 (annual probability exceedance of 1/2500). The site-specific design spectral values (S(Ta)) are calculated from the PGA to determine the base shear. For the initial analysis, the R_o and R_d shall be taken from Table 4.1.8.9 of NBCC2015 for timber walls.

A Direct Displacement Based Design (DDBD) procedure is used to specify the RSFJs (Hashemi, Masoudnia, and Quenneville 2016). In this procedure, the structure is represented as an elastic Single Degree of Freedom structure (SDOF) with effective stiffness and effective period to predict the inelastic response. The pushover curves are generated for the structure using the two critical load patterns. These Pushover capacity curves for the building is then converted to SDOF pushover to produce the demand Acceleration Displacement Response Spectra (ADRS) curves (Lagaros and Fragiadakis 2011).

When both capacity curves intersect the scaled demand spectrum, the performance points are interpolated to determine the building performance and calculate the base shear. Accordingly, the equivalent R_d factor is determined to design the RSFJs. Note that RSFJs can be designed for various levels of damping as per the demand of the structure and various values of Rd as per the required performance. Figure 7 displays the capacity curves and the performance points.

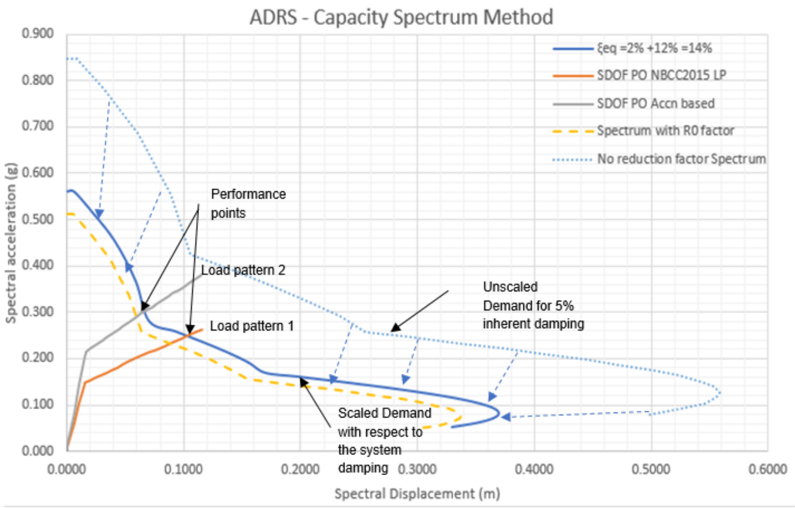


Figure 7: Capacity and performance curves

A potential difficulty with the pushover analysis is that it represents a static distribution of the seismic forces acting on the frame. Conventionally, an inverted triangular distribution of lateral seismic forces up the height of the frame could be assumed (as per FEMA 356 (Walls 2004)), but this approach does not consider higher mode effects or changes in displaced shape post-yield. Accordingly, two load patterns were considered for the analysis (see Figure 8).

5 PERFORMANCE TESTING OF THE HOLDODWN UNITS

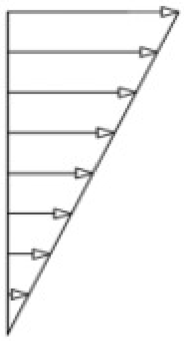
Based on the designed approach discussed above and to achieve the desired performance, the following characterises have been specified for the hold-downs:

Table 1: Summary of the significant test properties

Ultimate force (F_{ult}) kN	650
Slip force (F_{slip}) kN	450
Slip displacement (Δ_{slip}) mm	2.0
Ultimate design displacement (Δ_{ult}) mm	45

The devices were fabricated and tested based on these specifications. The testing was done using a loading speed of 1 mm/sec speed with three full cycles of loading and unloading to make sure that the hysteretic curves are stable and repeatable. Figure 7 demonstrates the cyclic test results related to one of the units as a representative for all four devices. As can be seen, the hysteretic performance of the devices is stable without any sign of stiffness or strength degradation. A self-centring characteristic is also observable from the test results. Considering the capacity design principal and the design philosophy used for this project, the CLT core was designed to remain elastic, and the ductility and damping are localised in the devices. Therefore, the core will also enjoy a self-centring behaviour (originated from the devices). The CLT core and other parts of the structure are designed using an over-strength factor of 1.5 (above the 1.35, which is the over strength-factor recommended for this system) to ensure that the desired hierarchy of strength is maintained (Bagheri et al. 2020).

Group 1 – Load pattern 1



- $T_{fundamental} \leq 1sec$
  1[st] mode Mass participation > 75%

$$F_x = (V - F_t)\,W_x h_x / \left(\sum_{i=1}^{n} W_i h_i\right)$$

… as per NBCC 2015 4.1.8.11.7

OR

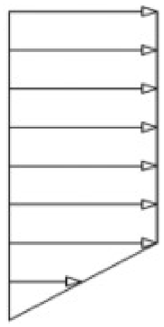
- 1[st] mode Mass participation > 75%
  Vertical distribution of lateral load proportional to fundamental mode shape

OR

- $T_{fundamental} > 1sec$
  1[st] mode Mass participation > 60%

  Vertical distribution of lateral load proportional to the storey shear distribution calculated by including enough modal response to capture at least 90% of the total building mass.

Group 2 – Load pattern 2



- Vertical distribution of lateral load proportional to the total mass at each level.

OR

- The load distribution must be changed from initial and applied according to the displaced yielded structure. (Adaptive Pushover)

Figure 8: Load patterns

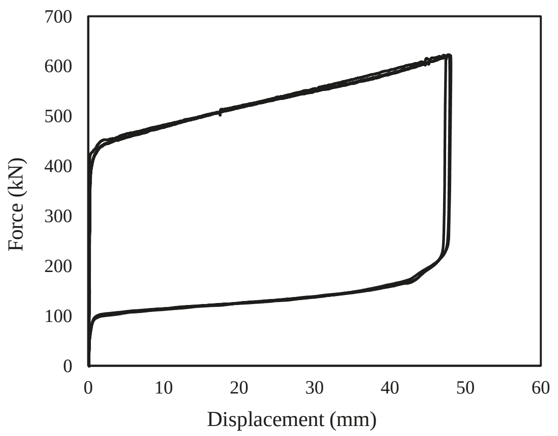


Figure 9: Performance testing of the hold-down units

6 CONCLUSIONS

This paper describes the oN5 building, an innovative mass timber project in Vancouver, Canada. The characteristics of the project, design philosophy, analysis method and lessons learned were described. This type of building is not explicitly covered by existing standards or guidelines. Therefore, such case studies can inspire researchers and engineers on how to analyse and design the system and, more importantly, how to deal with the seismic demand and come up with a low damage solution. For this case study, a rocking CLT core with resilient tension-only hold-down connectors was considered as the main lateral load resisting system. The controlled rocking mechanism ensures a low damage performance with a self-centring behaviour as an added advantage. The devices were performance-tested before installation to make sure that their behaviour was in line with the design assumptions.

7 REFERENCES

Bagheri, Hamed, Ashkan Hashemi, Pouyan Zarnani, and Pierre Quenneville. 2020. "The Resilient Slip Friction Joint Tension-Only Brace beyond Its Ultimate Level." *Journal of Constructional Steel Research* 172:106225.

Ceccotti, Ario, Carmen Sandhaas, Minoru Okabe, Motoi Yasumura, Chikahiro Minowa, and Naohito Kawai. 2013. "SOFIE Project–3D Shaking Table Test on a Seven Storey Full Scale Cross Laminated Timber Building." *Earthquake Engineering & Structural Dynamics* 42(13):2003–21.

Hashemi, Ashkan, Hamed Bagheri, Seyed Mohammad Mehdi Yousef-Beik, Farhad Mohammadi Darani, Armin Valadbeigi, Pouyan Zarnani, and Pierre Quenneville. 2020. "Enhanced Seismic Performance of Timber Structures Using Resilient Connections: Full-Scale Testing and Design Procedure." *Journal of Structural Engineering* 146(9):04020180.

Hashemi, Ashkan, Reza Masoudnia, and Pierre Quenneville. 2016. "Seismic Performance of Hybrid Self-Centring Steel-Timber Rocking Core Walls with Slip Friction Connections." *Journal of Constructional Steel Research* 126:201–13.

Hashemi, Ashkan, Pouyan Zarnani, Reza Masoudnia, and Pierre Quenneville. 2017. "Experimental Testing of Rocking Cross Laminated Timber (CLT) Walls with Resilient Slip Friction (RSF) Joints." *Journal of Structural Engineering* 144(1):04017180–81 to 04017180–16.

Karacabeyli, Erol, Brad Douglas, and Binational Softwood Lumber Council. 2013. *CLT Handbook: Cross-Laminated Timber*. FPInnovations.

Lagaros, Nikos D. and Michalis Fragiadakis. 2011. "Evaluation of ASCE-41, ATC-40 and N2 Static Pushover Methods Based on Optimally Designed Buildings." *Soil Dynamics and Earthquake Engineering* 31(1):77–90.

Popovski, Marjan and Igor Gavric. 2015. "Performance of a 2-Story CLT House Subjected to Lateral Loads." *Journal of Structural Engineering* E4015006.

Tannert, Thomas. 2019. "Design Provisions for Cross-Laminated Timber Structures." Pp. 171–78 in *Structures Congress 2019: Buildings and Natural Disasters*. American Society of Civil Engineers Reston, VA.

Tremblay, Robert, Gail M. Atkinson, Najib Bouaanani, Poulad Daneshvar, Pierre Léger, and Sanda Koboevic. 2015. "Selection and Scaling of Ground Motion Time Histories for Seismic Analysis Using NBCC 2015." in *11th Canadian Conference on Earthquake Engineering (11CCEE), Victoria, BC, Canada*. Vol. 99060.

Walls, Stone Masonry. 2004. "FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings, ASCE for the Federal Emergency Management Agency, Washington, DC, November 2000. Forghani R., Totoev YZ y Kanjanabootra S., Experimental Investigation of the Water Penetratio." *Masonry Society Journal* 25(1):41–52.

Yasumura, Motoi, Kenji Kobayashi, Minoru Okabe, Tatsuya Miyake, and Kazuyuki Matsumoto. 2015. "Full-Scale Tests and Numerical Analysis of Low-Rise CLT Structures under Lateral Loading." *Journal of Structural Engineering* E4015007.