CSCE 2022 Annual Conference
Whistler, British Columbia
May 25th – 28th, 2022

SEISMIC ASSESSMENT OF BALLOON-FRAMED CROSS-LAMINATED TIMBER SCHOOL BUILDING

Pan, Yuxin[1,5], Jafari, Maral[2], Shahnewaz, Md[3] and Tannert, Thomas[4]

[1] Postdoctoral Fellow, School of Engineering, University of Northern British Columbia, Prince George, BC, Canada
[2] Graduate Research Assistant, School of Engineering, University of Northern British Columbia, Prince George, BC, Canada
[3] Specialist Engineer, Fast+Epp, Vancouver, BC, Canada (presenter)
[4] Professor, School of Engineering, University of Northern British Columbia, Prince George, BC, Canada
[5] ypan@civil.ubc.ca

Abstract: Cross-laminated timber (CLT) has become popular for its material properties and associated environmental benefits. CLT panels, either using platform-type or balloon-framed methods, can be utilized as part of the lateral load resisting system. In this paper, the seismic performance of a two-story balloon frame CLT school building was investigated. The building was designed for a Vancouver site based on the 2015 National Building Code of Canada seismic provisions. A three-dimensional finite element model of the building was developed in OpenSees where the energy-dissipative connections (i.e., hold-down, spline joint, etc.) were modeled and calibrated against tests. To properly account for the local seismic hazard, a probabilistic seismic hazard analysis was conducted for the building site to select ground motion records for shallow crustal earthquakes, subduction inslab and interface earthquakes. Incremental dynamic analyses were carried out to derive fragility curves for different drift limits and collapse capacity with respect to different intensity levels. The results at the design intensity level showed a maximum inter-storey drift ratio of 0.51% on average for both directions, well below the applicable 2% drift limit. The median collapse capacity was determined as 2.41 g. Considering the design intensity of 0.76 g, a collapse margin ratio of 3.18 was calculated.

1 INTRODUCTION

Cross-laminated timber (CLT) panels are made of three or more layers of orthogonally glued dimensional lumbers (Brandner et al. 2016). Compared to concrete and steel, CLT has a lower environmental footprint (Karacabeyli and Gagnon 2019). The high stiffness and high strength-to-weight ratio its use as shear walls and diaphragms in multi-storey buildings to resist lateral loads (e.g., earthquakes), also in high-seismic zones (Tannert et al. 2018).

There are two common construction methods for the CLT buildings, namely platform-type and balloon-framed. In platform assemblies, each floor is a platform for the story above with the walls attached to the floors. Wall-to-floor connections are provided with hold-downs (HD) and wall base (WB) shear brackets using nails or self-tapping screws (STS), and wall-to-wall connections are provided with either spline joints or half-lap joints. In balloon-frame construction, the walls are continuous over multiple storeys or along the entire height of the building. The number of shear walls in balloon-frame structure is usually lower, which greatly reduces the number of required connections. However, only limited studies on the balloon-frame CLT building have been reported, e.g., Pei et al. (2019), Li et al. (2020), Chen and Popovski (2020), and Shahnewaz et al. (2021). To date, the seismic fragility and collapse risk for balloon-type CLT buildings has not been assessed.

The Begbie Elementary School, located in Vancouver, Canada was designed using balloon-framed CLT shear walls and CLT diaphragms as part of the lateral loading resisting system. The objective of the research presented herein was to quantify the nonlinear seismic responses of the balloon-framed CLT building by performing non-linear time history analyses (NLTHA) and evaluate its damage potential through Incremental Dynamic Analyses (IDA).

2 BUILDING DESCRIPTION

Herein, the north tower of the Begbie Elementary School building, see Figure 1a, was investigated. The storey heights for the first and second floor are 4.35 m and 4.0 m, respectively. The walls are balloon-framed with ledgers attached at the mid-height to support the intermediate floor. The building was designed with a live load of 2.4 kPa and a superimposed dead load of 2.5 kPa that includes non-structural architectural topping, partitions, and finishes. The seismic design of the building was based on 2015 National Building Code of Canada (NBCC) (NBCC 2015) for Site Class C. For elementary school building, a high important factor I_E of 1.3 is applied, with seismic reduction factors R_d of 2.0 and R_o of 1.5, respectively.

The CLT walls were detailed with capacity protected wall base connections. Notched glulam sill plates were anchored on the concrete footing to support the wall panels with Ø10x140 mm partially threaded screws with washer heads (PSW) spaced from 65 mm to 300 mm. For energy dissipative connections, there were 11 types of HDs and 12 types of panel-to-panel joints (SP) designed for the whole building. HD1-3 are WHT angle plates with different numbers of anker nails, while HD4/5 are made of 13 mm thick customized stainless steel internal plates installed with Ø12mm tight fit pins. The SP1-3 are provided with 25 mm by 140 mm D.Fir plywood surface-splines mounted with 2 types of fasteners (PSW and smooth shank nails) at different spacings. SP7-9 are half-lap joint connections with 80 mm lap length and partially threaded screws with hex heads (PSH). SP11 was a half lap joint of 200 mm lap length combined with a steel connector plate, which was used for corners of openings with 2 rows of PSH screws. Figure 1b shows the wall assembly at the construction site.

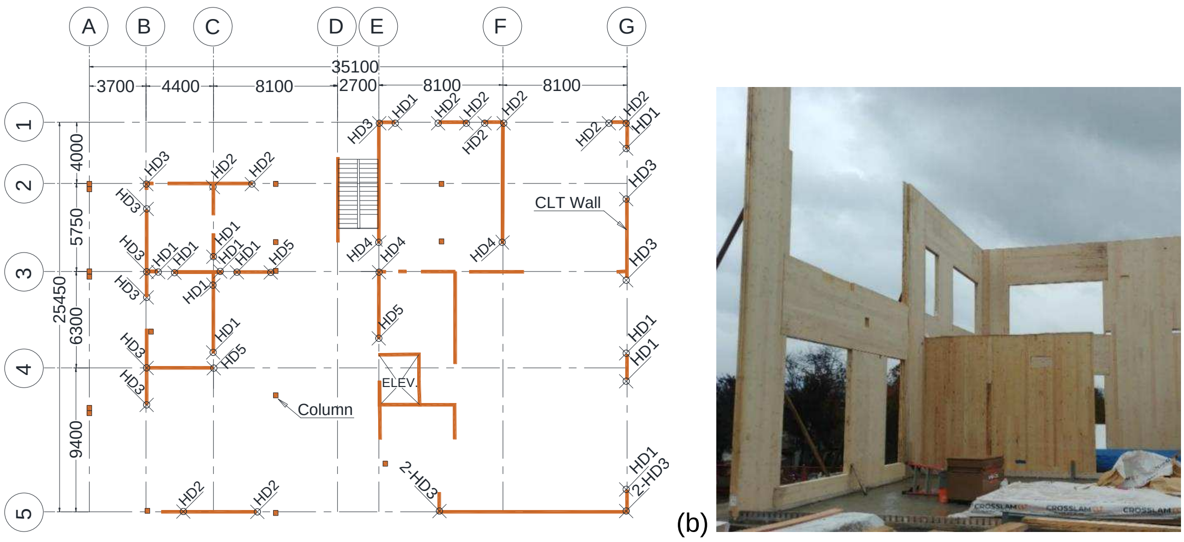
(a)


Figure 1: Floor plans of the north tower (a) and construction site photo (b)

3 NUMERICAL MODELING

The nonlinear 3D building model was developed in OpenSees (Mazzoni et al. 2006). The model consists of shell elements that simulate the CLT wall panels and nonlinear springs that simulate the wall-to-foundation and wall-to-wall connections. An isotropic elastic material was adopted for the shellMITC4 element to model the CLT walls as the nonlinearity of CLT shear walls is concentrated in the connections (Rinaldin and Fragiacomo 2016). Two types of nonlinear spring elements were used for model the connections: 1) HD and WB were modeled with zeroLength element; and 2) SP were modeled with twoNodeLink elements, both with independent behavior along three local axes (tension, shear, and out-of-plane). The floor and the roof were assumed as rigid diaphragm with mass lumped at each storey. The first two fundamental periods (*T*) of the nonlinear building model at both translational directions were determined as 0.46 s and 0.44 s.

To account for the nonlinear behavior of connections at large deformations, including pinching effect and degradation in stiffness and strength, a nonlinear Pinching4 material model in OpenSees was used. The HDs were designed to resist uplift only, so each HD was assigned with one Pinching4 model in the vertical direction. To simulate the contact compression behavior at panel edge, an elastic-no-tension (ENT) material model with large compression stiffness was introduced in parallel with the tension spring of the HD. The WB connections were modeled using two orthogonal springs to simulate both tension and shear resistances. The pinching4 hysteresis parameters for each connection were calibrated with experimental tests. For brevity, herein only the half-lap joint model SP7-9 is illustrated in Figure 2a. Then, the calibrated connection models were validated by simulating the nonlinear response of a full-scale balloon-framed CLT shear wall tested under reversed cyclic loading, see Figure 2b. Good agreement of the nonlinear hysteresis curve was achieved between the model and the test data.

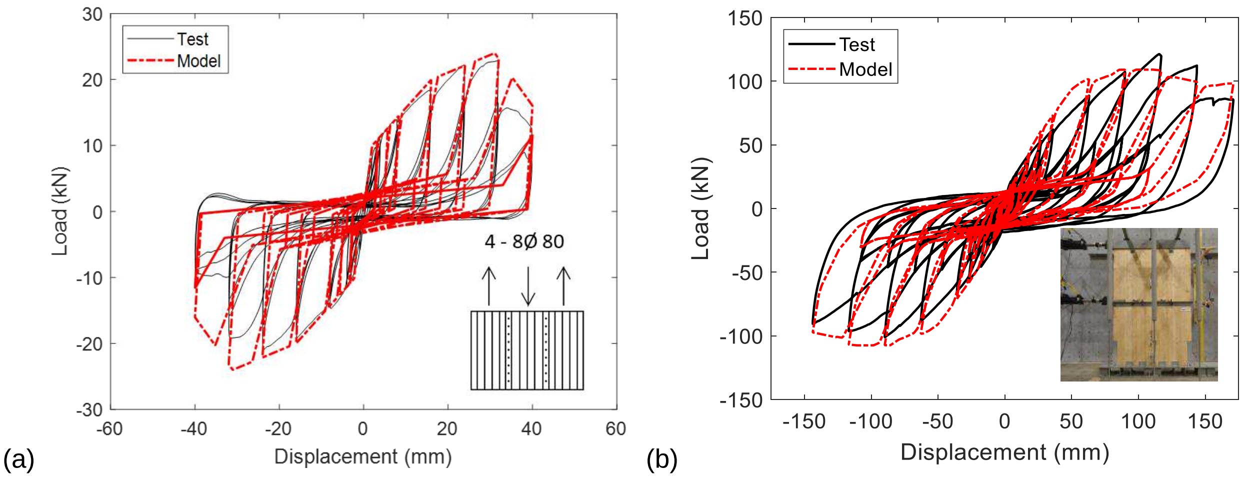


Figure 2: Test versus model: (a) spline joint, (b) shear wall

4 GROUND MOTION SELECTION AND SCALING

To perform NLTHA and IDA on a 3D model, appropriate bi-directional ground motion records that represent the characteristic seismicity of the location need to be selected. To evaluate the seismic hazard of the region, a probabilistic seismic hazard analysis (PSHA) was conducted. Based on the PSHA results, the PEER NGA-West 2 database (PEER 2013) was used to retrieve crustal records, while the 7 subduction inslab and 7 interface records were selected from the K-NET/KiK-net (K-net 2012) and COSMOS (COSMOS 2011) databases. In accordance with the 2015 NBCC, all 21 records were linearly scaled to match the target uniform hazard spectrum (UHS) for the Vancouver site with Class C over a period range of 0.2*T* to 2.0*T*, where *T* is the building's fundamental period. Figure 3 shows the response spectra of all selected motions and their mean spectrum matched to the Vancouver UHS.

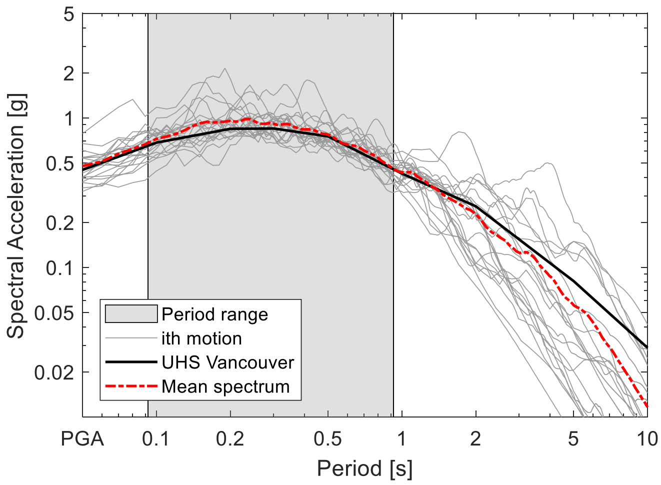


Figure 3: Response spectra of selected motions matched to the target spectrum

5 RESULTS

Figure 4 shows the maximum inter-storey drift (*IDR*s) of the building for each individual ground motion and the mean value. The maximum IDRs on average was 0.51% at the first storey for both directions, which was below the 2% drift limit specified in NBCC for elementary school of high importance. Looking at the impact of the earthquake type, the subduction inslab motions generated the largest *IDR* (0.56%) at the primary E-W direction, which was 21% and 10% higher than those from the crustal and subduction interface motions, respectively.

IDA was performed for each bidirectional ground motion pair scaled from 20% to 400% (IM_{max}) of the UHS design intensity with a 20% increment. In total, 420 NLTHA (3 sets of 7 motions at 20 intensity levels) were conducted. For the 3D model, the maximum inter-storey drift (IDR_{max}) of the building was recorded. Figure 5 shows the IDA curves of the building model subjected to 21 ground motions of varying intensities and their median value. At the design intensity level (100% of UHS), the maximum drifts were less than 1%.

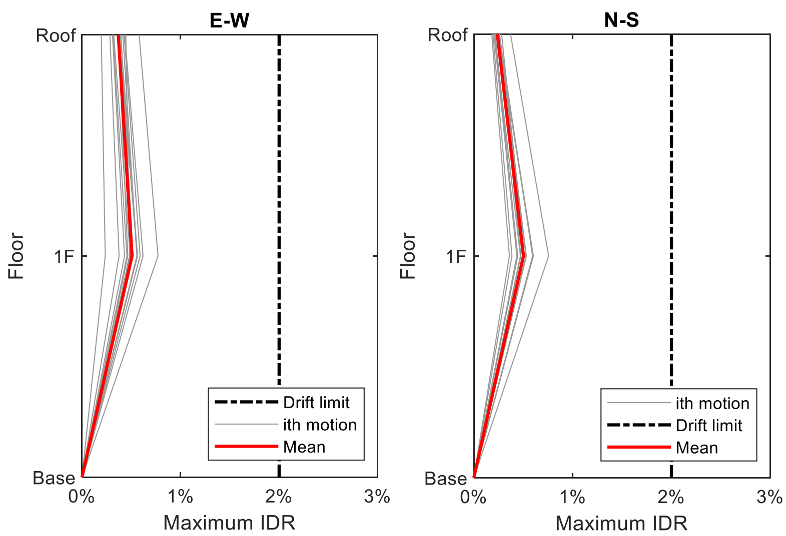


Figure 4: Maximum inter-storey drift ratio (*IDR*) at design intensity level

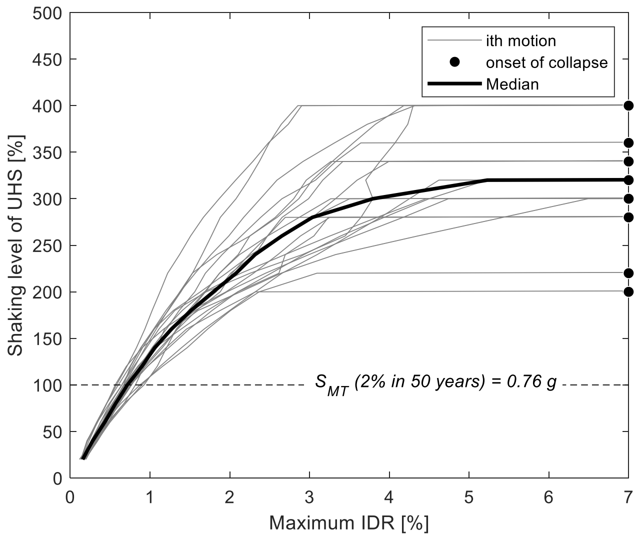


Figure 5: IDA curves of all ground motions

Based on the IDA, the collapse fragility curve was developed, see Figure 6. The red line is the CDF by fitting a lognormal distribution through the empirical collapse data points (black dots). The median collapse capacity (50% probability of collapse) was determined at IM of S_{CT} = 2.41 g (i.e., 320% of UHS). Considering the design intensity of S_{MT} = 0.76 g, the CMR was calculated as 3.18 for the Begbie building model.

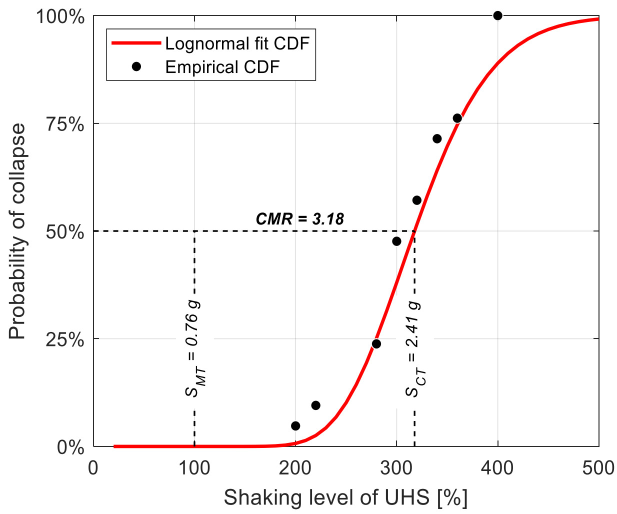


Figure 6: Fragility curve for collapse with uncertainty

6 CONCLUSIONS

This study investigated the seismic performance and collapse capacity of an actual two-storey CLT balloon-framed school building. NLTHA of selected motions at the design earthquake level (2% in 50 years) were first conducted. Subsequently, IDA were performed to derive fragility curves for collapse capacity and drift exceedance. Based on the analysis results, the building model (north tower) met the seismic design criterion for Vancouver with the maximum drift below the 2% limit for a 2475-year return period earthquake hazard.

Acknowledgements

The project was supported by Natural Resources Canada (NRCAN) through the Green Construction Wood (GCWood) program and by the Government of Canada through a Canada Research Chair.

References

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., and Thiel, A. 2016. Cross laminated timber (CLT): overview and development. *European Journal of Wood and Wood Products*, 74(3), 331-351.

Chen, Z., and Popovski, M. 2020. Mechanics-based analytical models for balloon-type cross-laminated timber (CLT) shear walls under lateral loads. *Engineering Structures*, 208, 109916.

COSMOS 2011. Global Component of the Center for Earthquake Strong Motion Data, Strong-Motion Virtual Data Center., <https://strongmotioncenter.org/vdc/scripts/default.plx>. (October, 2021).

K-net 2012. Strong-motion seismograph networks (k-net, kik-net). <http://www.k-net.bosai.go.jp/>. (October, 2021).

Karacabeyli, E., and Gagnon, S. 2019. *Canadian CLT Handbook, 2019 Edition*. FPInnovations, Pointe-Claire, QC, Canada.

Li, Z., Wang, X., and He, M. 2020. Experimental and analytical investigations into lateral performance of cross-laminated timber (CLT) shear walls with different construction methods. *Journal of Earthquake Engineering*, 1-23.

Mazzoni, S., McKenna, F., Scott, M. H., and Fenves, G. L. 2006. OpenSees command language manual, Pacific Earthquake Engineering Research (PEER) Center. Berkeley, CA, 137-158.

NBCC 2015. *National Building Code of Canada, Canadian Commission on Building and Fire Codes*. National Research Council of Canada, Ottawa, Ontario, Canada.

PEER 2013. Pacific Earthquake Engineering Research (PEER) NGA-West2 Database. <https://ngawest2.berkeley.edu/>. (October, 2021).

Pei, S., van de Lindt, J. W., Barbosa, et al. 2019. Experimental seismic response of a resilient 2-story mass-timber building with post-tensioned rocking walls. *Journal of Structural Engineering*, 145(11), 04019120.

Rinaldin, G., and Fragiacomo, M. 2016. Non-linear simulation of shaking-table tests on 3-and 7-storey X-Lam timber buildings. *Engineering Structures*, 113, 133-148.

Shahnewaz, M., Dickof, C., and Tannert, T. 2021. Seismic Behavior of Balloon Frame CLT Shear Walls with Different Ledgers. *Journal of Structural Engineering*, 147(9), 04021137.

Tannert, T., Follesa, M., Fragiacomo, M, et al. 2018. Seismic design of cross-laminated timber buildings. *Wood and Fiber Science*, 3-26.