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Seismic Fragility Assessment of a Balloon-framed CLT Building with Self-centering Hold-down

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ABSTRACT

Balloon-framed cross-laminated timber (CLT) construction offers several advantages over platform-type construction. However, limited studies have been conducted on the seismic performance of balloon-framed CLT buildings during earthquake shaking, and many building codes only apply to platform-type construction. Furthermore, the use of innovative self-centering, energy-dissipation devices in balloon-framed CLT buildings is not yet well understood. In this study, the seismic performance of a balloon-framed CLT building that incorporates friction-based self-centering hold-downs (HDs) was evaluated. A three-dimensional (3D) nonlinear finite element model was developed, with the connections calibrated using test data. A tri-hazard ground motion selection approach was used to select and scale appropriate earthquake motions for the building site in Vancouver, Canada. The seismic performance and damage potential of the building were assessed through nonlinear time history analysis (NLTHA) and incremental dynamic analyses (IDA). The results of the NLTHA at the design intensity level showed that the building had an average maximum inter-story drift ratio of 0.67%. From the IDA, a collapse margin ratio of 2.96 was calculated for the building model, indicating satisfactory seismic performance.

Keywords: Cross-laminated timber, seismic fragility, self-centering, incremental dynamic analysis, resilience

INTRODUCTION

Background

In most CLT projects, a platform-type approach has been utilized, in which each floor serves as a platform for the next floor [1]. However, this method has several disadvantages, including the requirement for high perpendicular-to-grain compression resistance of the base floor, and the need for more time for on-site assembly [2]. To address these issues, balloon-framed construction has been proposed, whereby the walls are continuous from the base to the roof with floors. Despite its potential advantages, limited studies are available on balloon-framed construction, and no design guidelines for this approach are specified in the Canadian Standard for Engineering Design in Wood CSA O86 [3]. One of the reasons is that the design of base connections for tall balloon-framed walls is a significant challenge, as they require larger shear and overturning resistances.

Resilient slip friction joint

In common CLT lateral load resisting systems, damage during earthquakes can occur due to yielding and nail withdrawal of steel connectors, such as spline joints, HDs, and shear connections [4]. Amongst the several high-performance connectors that have been developed in recent years [5], a friction-based self-centering device used as HD has shown great energy dissipation while causing low damage. The technology, commercially available under the trademark 'Tectonus', was used in a recently completed balloon-framed building, the office of the engineering firm Fast + Epp, located in Vancouver, Canada [20], as shown in Figure 1.

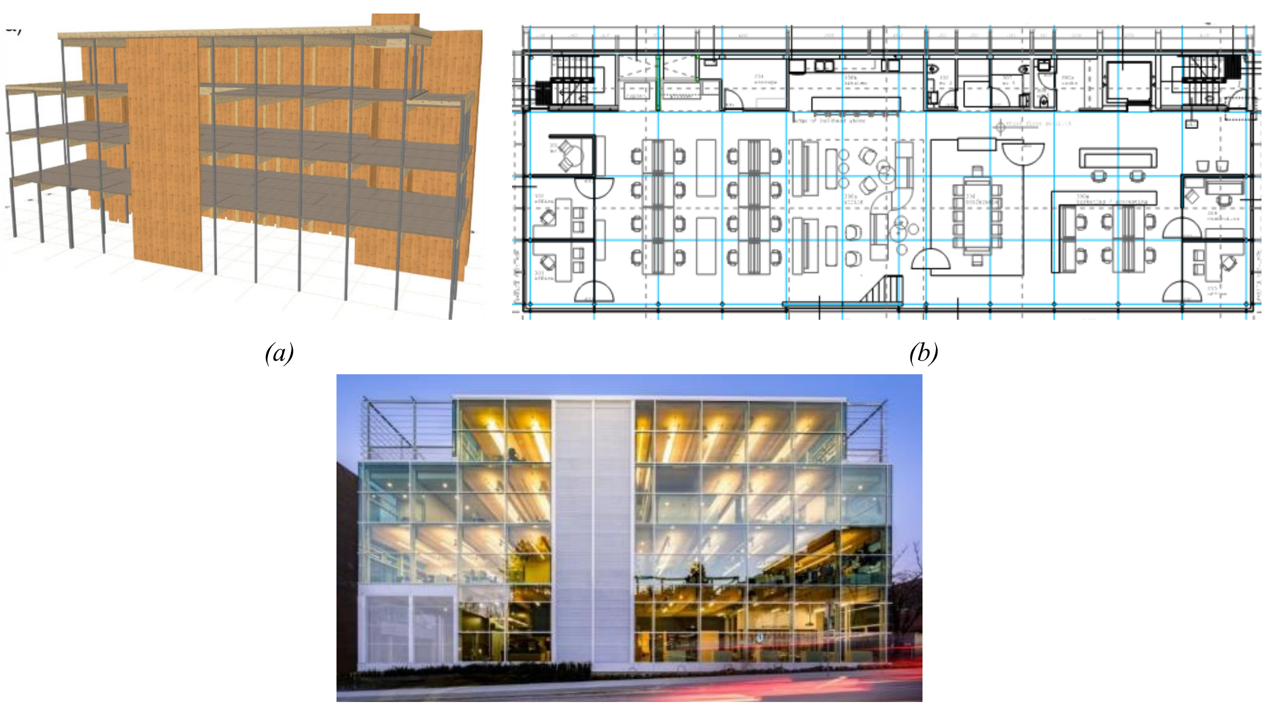
Figure 1. Photo of the installed Tectonus HD

Objective

It is of value to understand the seismic performance and effectiveness of the friction-based self-centering device used for the first time in North America in a high-seismic region and in a balloon-framed CLT structure. To achieve this objective, NLTHA were conducted, and the seismic collapse fragility of this balloon-framed building was quantified, and the energy-dissipation and self-centering capacity of the self-centering device was evaluated. First, a 3D numerical model of the structure was developed. Then, the seismic fragility was evaluated according to the FEMA P695 approach, applying a tri-hazard procedure for selecting ground motions. Lastly, IDA was performed to quantify the seismic fragility of collapse and drift exceedance of the building.

BUILDING DESCRIPTION

The 4-storey, 16 m tall CLT building, located in Vancouver, Canada, has a floor plan of 36.8 m×11.4 m, as shown in Figure 2. The building was designed with a live load of 2.4 kPa and a superimposed dead load of 2.5 kPa. The 2015 version of National Building Code of Canada (NBCC) [6] was used for the seismic design for a Class B Vancouver site. Seismic design reduction factors Rd and Ro of 2.0 and 1.5, respectively were used for the lateral system design which corresponds to the requirement for rocking platform-type CLT shear walls [3].



(a) *(b)*

(c)

Figure 2. CLT building: (a) 3D view, (b) plan view, (c) photo.

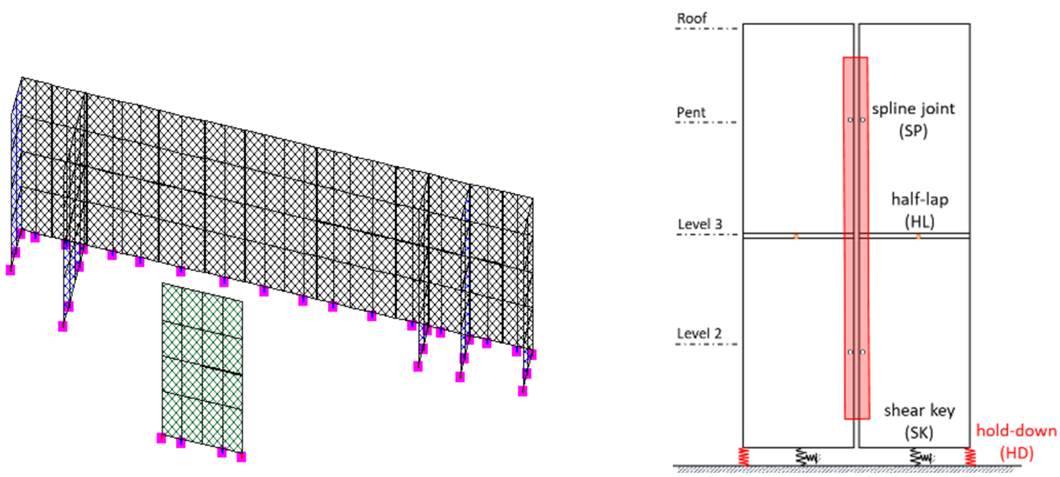
CLT is utilized throughout the building for the floors, elevator cores, as well as the demising firewall. The walls are balloon-framed for every two storeys connected with $\phi 8\times 130$ mm fully threaded screws installed in horizontal half-lap joints. The vertical panel-to-panel connections are provided with 19 mm ×200 mm D. Fir plywood surface spline joints using both partially threaded screws and smooth shank nails at a spacing of 500 mm and 64 mm, respectively.

Base connections include concrete shear keys for each panel and two Tectonus HD at both ends of the coupled walls. The Tectonus HD act as shock absorbers for the building during an earthquake, providing energy dissipation and damping through the earthquake cycles, with the ability to snap back to its original position once shaking ends. The Tectonus connectors remain damage-free, a feature that might allow immediate return to occupancy after a significant earthquake, without facing uncertain delays expected with conventional systems.

MODELING AND ANALYSIS

Model development

A nonlinear 3D model of the building was developed in OpenSees [7], following the approach presented by Pan et al. [8]. Isotropic elastic shell elements were used for the CLT panels and nonlinear spring elements (either zeroLength or twoNodeLink) were used to simulate the connections, as shown in Figure 3a. Pinching4 model and *SelfCentering* models were used and calibrated to represent the nonlinear behaviour of the connections, including cyclic degradation and pinching at large deformation. A schematic of a typical coupled balloon-framed CLT shear wall is illustrated in Figure 3b.



(a) *(b)*

Figure 3. OpenSees building model: (a) 3D model, (b) 2D balloon-framed CLT shear wall model.

Model calibration

All nonlinear connections were calibrated with experimental test data [9, 10]. For the Tectonus HD, the design values were used to calibrate the *SelfCentering* material model. An equivalent energy rule was introduced, by adjusting the ratio of forward to reverse activation force β, the hysteresis energy defined as the area enclosed by the numerical backbone curves is as close as possible to the area enclosed by the design parameter (black), see Figure 4.

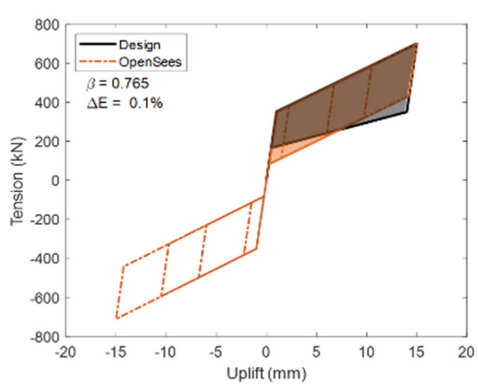


Figure 4. Calibration for Tectonus HD.

Analysis and ground motion selection

For a new building system for which there is no damage or experimental data available, it is recommended to follow the FEMA P695 [11] to assess its seismic performance and collapse fragility. In this approach, IDA is adopted to derive the fragility curve – a function between building's damage state with the earthquake intensity measure. Inter-storey drift ratio (IDR) and spectral acceleration at building's period are typical damage and intensity measures, respectively. In IDA, as an input for NLTHA of the model, each selected ground motion record is scaled from low intensity to high intensity until structural collapse occurs. This procedure involves the criterion of the collapse and the selection and scaling of representative ground motions.

Appropriate ground motion records had to be selected as the inputs for the subsequent NLTHA and the IDA. Vancouver is located in the Cascadia Subduction Zone where three earthquake types contribute to the hazard: i) shallow crustal earthquakes; ii) subduction inslab earthquakes; and iii) subduction interface earthquakes [12]. The ground motion selection should reflect all three earthquakes; therefore, a probabilistic seismic hazard analysis (PSHA) was conducted to evaluate the probability of occurrence of all seismic sources surrounding the site based on their return periods. As specified by the NBCC [6], all 21 selected records were linearly scaled to match the target uniform hazard spectrum (UHS) for the Vancouver site with Class B over a period range $0.2T$ to $2.0T$, where T is the first mode period. The response spectra of all selected motions and their mean spectrum matched to the Vancouver UHS are shown in Figure 5.

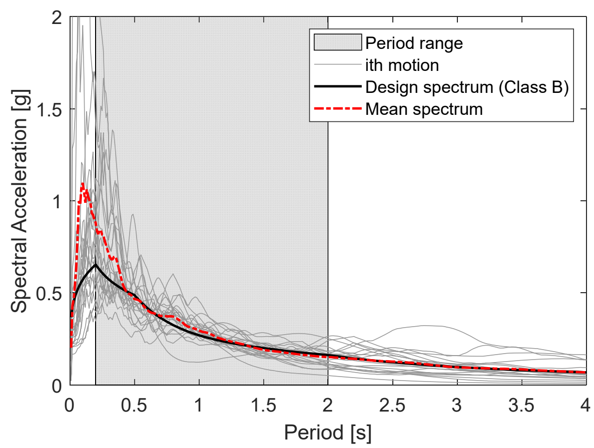


Figure 5. Ground motion selection and scaling.

RESULTS

Modal analysis

The first three mode shapes of the developed model are shown in Figure 6. The building had a fundamental period of 0.8 sec in the short direction (East-West) and 0.5 sec in the long direction (North-South). The third mode is the second translation mode in the short direction with a period of 0.3 sec. Sliding and rocking behaviour of the CLT panels can be clearly identified.

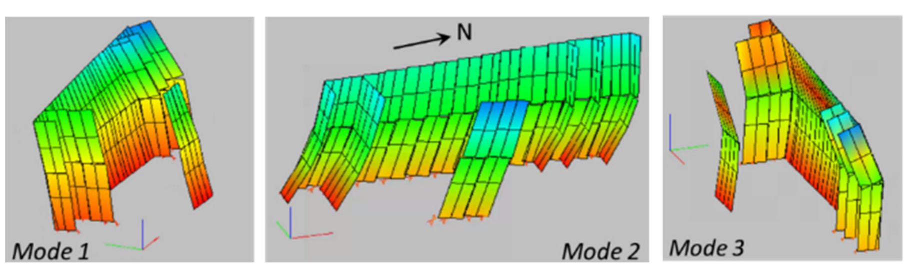


Figure 6. Mode shapes of the building model.

Nonlinear time history analyses at design level

The IDR for each ground motion and the mean value obtained are illustrated in Figure 7. The maximum IDRs on average were 0.22% at the second story for the long X direction (North-South) and 0.67% at the roof floor for the short Y direction (East-West), well below the 2.5% drift limit specified in NBCC [6] for normal importance category buildings. Although the building was more flexible in the short E-W direction, it experienced no residual displacement in this direction, caused by the self-centering characteristics of the Tectonus HDs installed in those short CLT walls.

Hysteresis curves of the Tectonus building model and representative connections subjected to the Michoacan inslab motion (station: Caleta De Campos) at design level are presented in Figure 8. Highly nonlinear behaviour including stiffness and strength degradation as well as pinching can be observed. It can be seen the panel-to-panel spline connection was the primary source for energy dissipation, followed by the Tectonus HD, which exhibited 2 mm uplift and 400 kN tension force for this design level shaking. The vertical floor connection was capacity protected, and therefor showed almost linear behaviour.

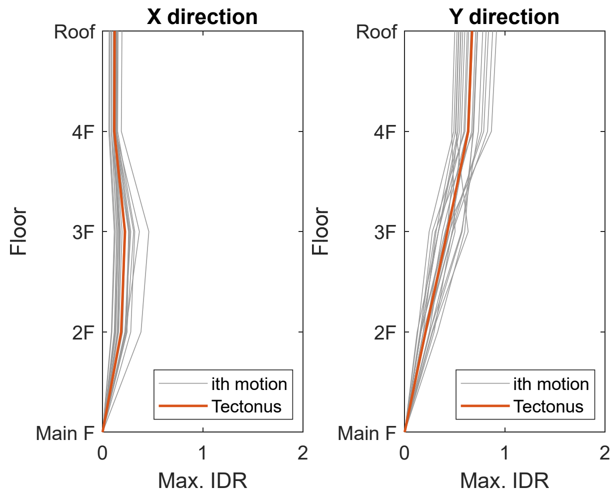


Figure 7: Maximum IDR at design level.

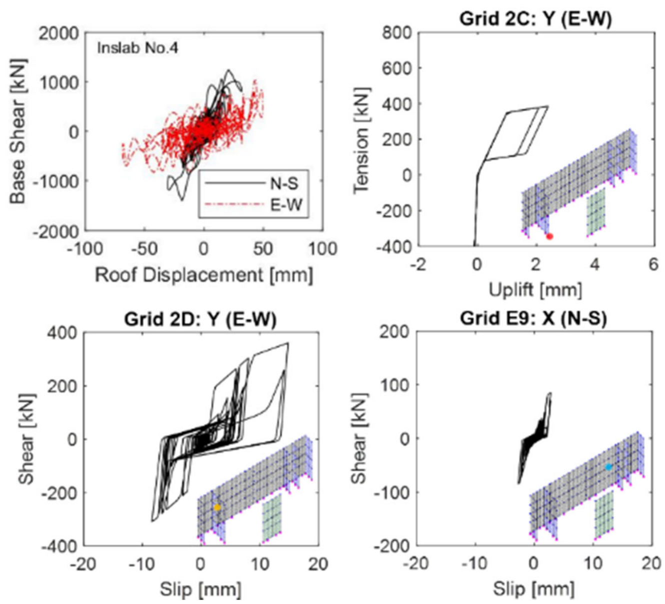


Figure 8: Nonlinear hysteresis curves of the building and connections during subduction inslab motion.

Incremental dynamic analysis

Next, IDA were performed to derive the fragility curves for two buildings. In the IDA, each ground motion was scaled for 20 intensity levels (from 20% to 400% of the UHS design intensity with a 20% increment), resulting in 420 NLTHA analyses. The resulting IDA curves of the building are illustrated in Figure 9. Considering a 5% IDR as collapse criterion for CLT buildings [13,14], each black dot on the curve represents the onset of collapse. With increasing intensity, the building model started to collapse under the subduction interface Hokkaido (No. 5) motion at 210% UHS. The largest drift before the collapse was monitored as 5% when subjected to the subduction interface Michoacan motion at 250% of UHS.

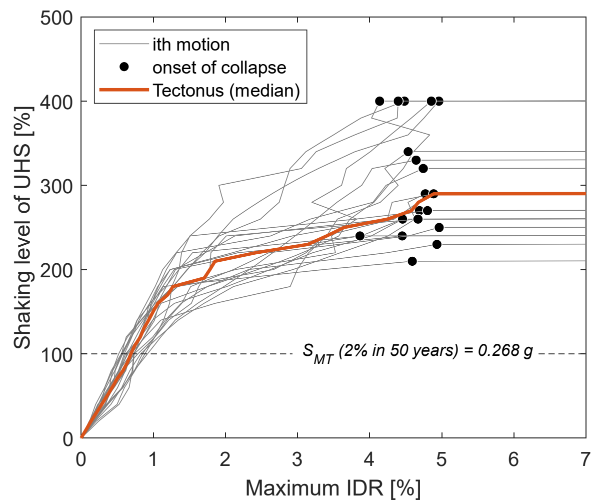


Figure 9: IDA curves of building model.

Fragility assessment

The fragility curve of collapse based on the IDA is presented in Figure 10. The median collapse capacity (50% probability of collapse) was determined at an intensity measure of S_{CT} = 0.793 g (296% of UHS). The collapse margin ratio was calculated as S_{CT}/S_{MT} =2.96 (considering the design intensity of S_{MT} = 0.268 g). The fragility curve with uncertainties was also plotted as dashed line. The uncertainty parameters were determined as follows: β_{DR} = 0.35 for a "fair" design with a medium level of confidence on basis of design requirements and a medium level of completeness and robustness; β_{TD} = 0.2 for "good" test data with sufficient testing conducted at the laboratory on both connections and shear walls; β_{TD} = 0.35 for "fair" numerical modelling since it covered most of the design space and was validated with cyclic test data; and β_{RTR} = 0.4 for a conservative record-to-record variability. Finally, an overall uncertainty β_{TOT} was calculated as 0.67 and the building had a 5.2% probability of collapse at the 2% in 50 years design level, meeting the requirement of less than 10% according to FEMA P695 [11].

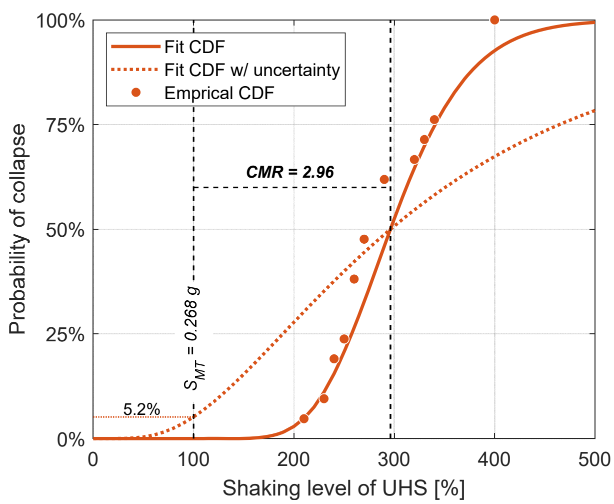


Figure 10: Collapse fragility curve with uncertainty.

CONCLUSIONS

A numerical seismic fragility assessment was conducted on a balloon-framed CLT structure, the first in North America adopting a resilient slip friction device – the Tectonus HD. A 3D nonlinear model of the building was developed and calibrated with experimental data. The innovative HD was modelled using a self-centering material model in OpenSees and calibrated following an energy equivalent rule. NLTHA and IDA were performed using motions selected based on a tri-hazard ground motion selection approach for the Cascadia Subduction Zone. Based on the results, the balloon-framed CLT building with the Tectonus HDs met the seismic design criterion for Vancouver with the maximum drift below the 2.5% limit. Considering uncertainties, a 5.2% probability of collapse was identified at design level with a collapse margin ratio of 2.96.

ACKNOWLEDGEMENT

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