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SEISMIC ASSESSMENT OF BALLOON-FRAMED CLT BUILDING WITH SELF-CENTERING HOLD-DOWN

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ABSTRACT: Balloon-framed cross-laminated timber (CLT) construction has a number of advantages when compared to platform-type construction. To date, however, only limited studies are reported on the performance of the former during earthquake shaking, and the seismic design provisions of many buildings codes only apply to the latter. Applications of innovative self-centering, energy-dissipation devices in balloon-framed CLT building are not yet well understood either. This study assesses the seismic performance of a balloon-framed CLT building with friction-based self-centering hold-downs (HD). A three-dimensional nonlinear finite element model was developed with the connections calibrated with test data. A tri-hazard ground motion selection approach was adopted to select and scale proper earthquake motions for the building site in Vancouver, Canada. The impact of the choice of hold-down on the seismic performance and damage potential of the building was assessed through nonlinear time history and incremental dynamic analyses. At design level, the building had an maximum drift of 0.67%, which met the 2.5% design limit. For comparison, a second building model with traditional HD was established and analysed, where larger drift was observed. The results confirmed the good seismic performance of the self-centering HD for balloon-framed CLT building.

KEYWORDS: Cross-laminated timber, seismic fragility, nonlinear modelling, resilience

1 INTRODUCTION

Most recent cross-laminated timber (CLT) projects applied a platform-type approach where each floor serves as a platform for erecting the walls of the next floor [1]. The platform construction has several disadvantages, mainly, it requires high compression resistance of the base floor in perpendicular-to-grain direction, and it requires more time for on-site assembly [2]. Balloon-framed construction, in which the walls are continuous from the base to the roof with floors can solve these problems. However, limited studies on balloon-framed construction are available and the design guideline for balloon-frame construction is not specified in Canadian Standard for Engineering Design in Wood CSA O86 [3].

A shake table tests on a 2-storey balloon-framed building with post-tensioned CLT rocking walls was conducted at UCSD laboratory [4]. It was observed that the building performed well at the maximum considered earthquake level. Li et al. [5] conducted a series of reversed cyclic tests on the balloon-framed shear walls and developed analytical equations for estimating the wall resistance. FPInnovations [6] in Canada proposed a mechanics-based model to predict the deflection and resistance of the balloon-type CLT building with an aspect ratio up to 12:1. Shahnewaz et al. [7] conducted static monotonic and cyclic tests on 2-storey balloon-framed CLT shear walls and identified that the rocking behavior of the CLT was not affected by the ledgers. Zhang et al. [8] developed 3D ETABS model for tall balloon-framed CLT building (12-story and 18-story) to investigate the influence of different connections on the overall characteristics of the building. Recently, Pan et al. [9] studied the collapse risk of a 2-storey school building retrofitted with balloon-framed CLT shear walls and found the building designed with the seismic reduction factors of that from the platform system can meet the requirement.

Another challenge for balloon-framed construction is the design of the tall walls' base connections, which require larger shear and overturning resistances. Common CLT buildings experience damage due to yielding and nail withdrawal of steel connectors (e.g., spline joint, hold-down, shear connections) during earthquake excitations, while the wall panels exhibit almost rigid behaviour [10]. With the increase of the wall height, larger demands will be posed to the base connectors, therefore, high-performance connectors are needed to accommodate this demand. Amongst the several high-performance connectors that have been developed in recent years [11],

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a friction-based self-centering device used as hold-down (HD), commercially available under the trademark 'Tectonus', has shown great energy dissipation while causing low damage. Hashemi et al. [12] conducted large-scale experimental test conducted on a rocking CLT wall with this self-centering HD device and demonstrated that this novel device showed excellent behaviour and can achieve a damage-avoidant and seismic-resilient design.

This paper aims to assess the seismic performance of a balloon-framed CLT building with such self-centering device through nonlinear time history analysis (NLTHA).

2 BUILDING DESCRIPTION

The 4-storey, 16 m tall CLT building, located in Vancouver, Canada, has a dimension of 36.8 m×11.4 m and story height of 3.6 m, as shown in Figure 1. The building is the new office centre for Fast + Epp. It 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) [13] was used for the seismic design for a Class B Vancouver site (rock conditions). The CLT walls were designed with different thickness - 139 mm and 190 mm for the long direction, and 245 mm for the short direction. The walls are balloon-framed with ledgers at the middle. Seismic design reduction factors R_d and R_o of 2.0 and 1.5, respectively were used for the lateral system design which corresponds to the requirement for rocking platform CLT wall [3]. CLT is also utilized throughout the building for the floors, stairwells, elevator cores, as well as the demising firewall.

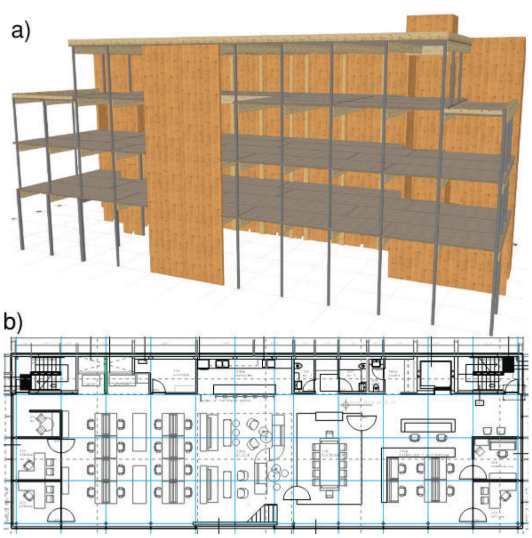

Figure 1: 3D isotropic a) and plan b) view of the building

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 (SK) for each panel and two Tectonus HD at both ends of the coupled walls. For SK, a concrete upstand of 250 mm height and 300 mm width was designed with 4-15M U-bars embedded.

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. Figure 2 shows a photo of the installed Tectonus device and a typical "flagshaped" hysteresis curve with self-centering characteristics. The design parameters are as follows: F_{slip}=350 kN, F_{ult}=700 kN, $F_{restoring}$=350 kN, $F_{residual}$=165 kN, and Δ_{ult}=15 mm.

In the original design, a steel braced frame was placed in the short direction of the building. As this study focused on the impact of the self-centering HD device, the building was modified by replacing the brace system with a coupled balloon-framed CLT shear wall. A total of 12 Tectonus HDs were used in the updated building model for assessment.

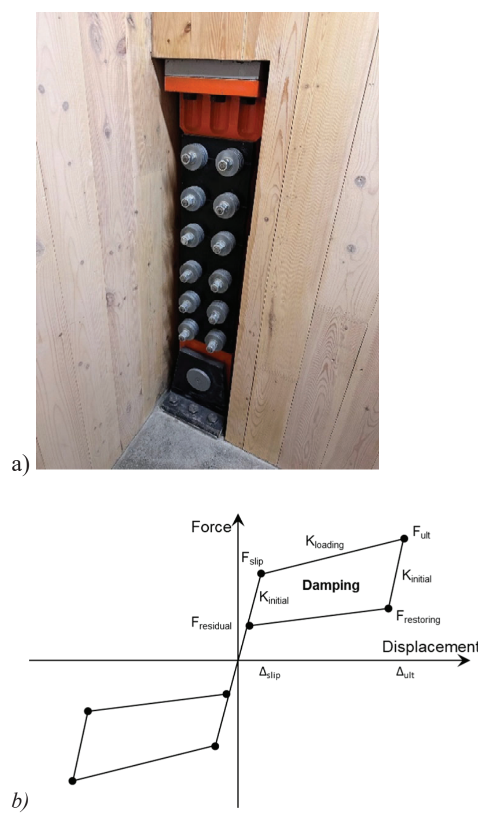

Figure 2: Tectonus HD device: a) photo, b) hysteresis curve

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3 MODELING

A nonlinear three-dimensional (3D) model of the building was developed in OpenSees [14]. Isotropic elastic shell elements were used to model the CLT wall panels and nonlinear spring elements (either zeroLength or twoNodeLink) were used to simulate the connections, as seen in Figure 3. Pinching4 model and SelfCentering models were used and calibrated to model the nonlinear behaviour of the connections, including cyclic degradation and pinching at large deformation.

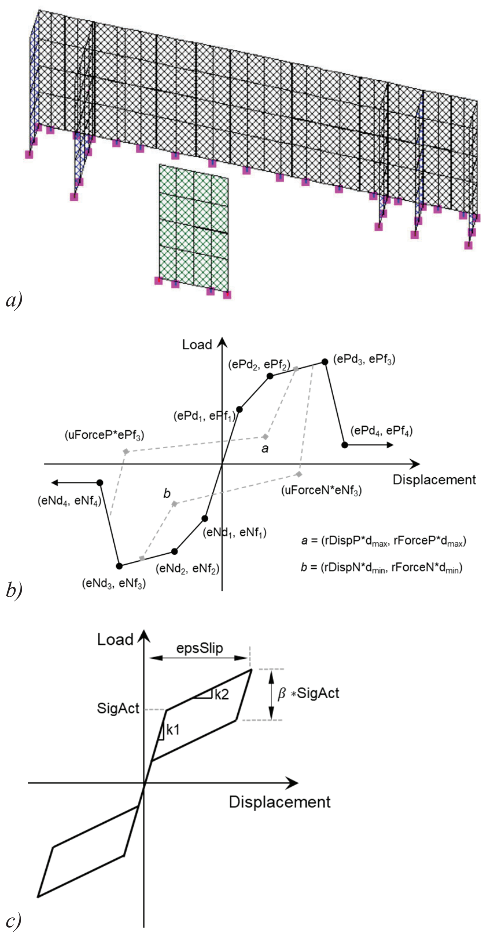


Figure 3: *Numerical model in OpenSees: a) 3D model of the building, b) Pinching4 material model, c) SelfCentering material model for connections*

For comparison purpose, a second building model with conventional dowel-type HD was established and modelled. The HD was manufactured with customized stell plate (975 mm high, 370 mm wide, 102 mm long at base, and 28 mm thick) and attached with 32 fully threaded $\phi 12\times 120$ self-tapping screws. It was tested at the UNBC lab with the same peak capacity of 700 kN.

All the connections were calibrated with experimental data available in the literature or conducted at UNBC lab. Considering the limitation of the SelfCentering model where the unloading stiffness has to be the same with the loading stiffness (different in actual behavior of the Tectous HD), an energy equivalent assumption was made: by controlling the *Frestoring* in Figure 2 (i.e., β in Figure 3b), the total energy enclosed by the numerical backbone curves was almost the same as the area enclosed by the design parameter.

Figure 4 shows the first two preliminary mode shapes of the developed model. The building had a fundamental period T of 0.8 sec in the short direction (East-West) and 0.5 sec in the long direction (North-South). The sliding and rocking behaviour of the CLT panels can be identified. The obtained information will be used to select proper ground motion input records that represent the seismicity for the nonlinear dynamic analysis.

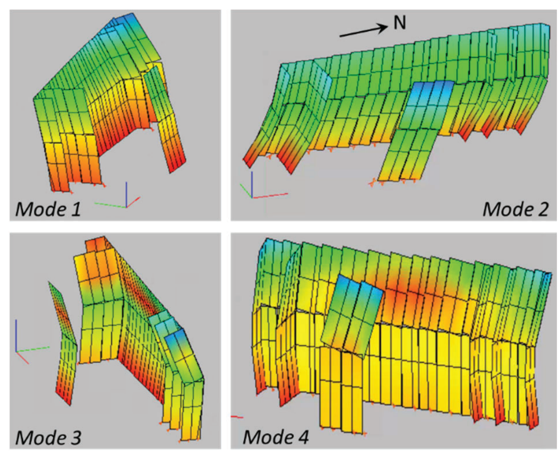


Figure 4: *Mode shapes of the building model*

4 ANALYSIS

To assess the seismic performance of the two buildings, NLTHA was performed on their models. This procedure requires proper selection and scaling of representative ground motions. For the building site of Vancouver, which is located in the complex Cascadia Subduction Zone, there are three types of earthquake hazards: 1) shallow crustal earthquakes, 2) subduction inslab earthquakes, and 3) subduction interface earthquakes. By conducting a probabilistic seismic hazard analysis for the site using Canada's 5th Generation Seismic Hazard Model, the contributions from each hazard are 8%, 72%, and 20%, respectively. As per the NBCC, a total of 21 pairs (two horizontal components) of ground motion records, 7 from each earthquake type, were selected from global databases and matched to the design spectrum of the building over a period range of 0.2T to 2.0T. Figure 5 shows the response spectra of selected motions matched to the design spectrum.

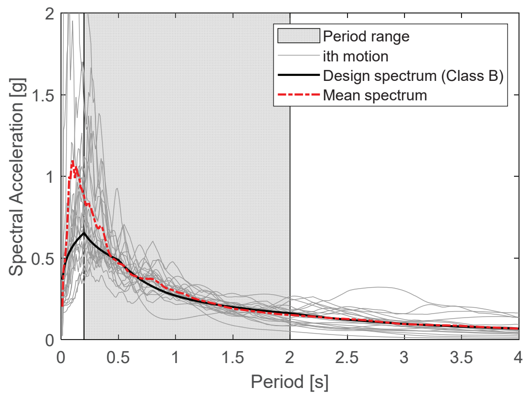
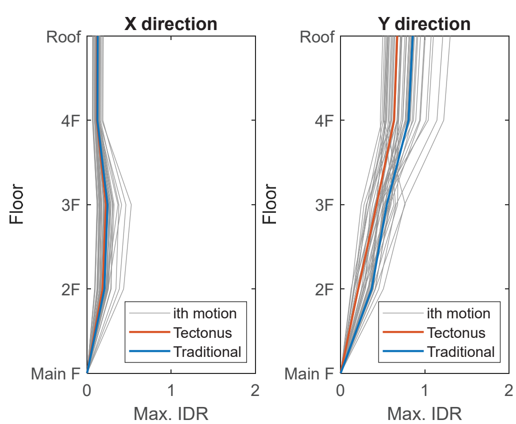
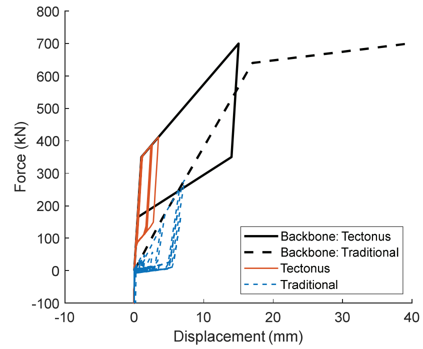


Figure 5: *Ground motion selection and scaling*

With the established models and the selected motios, NLTHA were conducted at the design intensity level for two building models. Figure 6a compares the maximum drifts at both directions of the buildings. For the Tectonus one, the maximum drift on average were 0.22% at the second story for the long direction and 0.67% at the roof floor for the short direction, which were far below the 2.5% drift limit specified in NBCC for normal importance category buildings. It was observed that the Tectonus HD had negligible impact on drift in the strong long direction, but decreased 30% drift for the short direction when compared to the conventional HD. It is worth mentioning that although the two HD devices had the same peak capacity, the initial stiffness were different, therefore, different seismic performance at design intensity levels were expected. This can be seen in Figure 6b. Due to lower initial stiffness, traditional HD showed twice the displacement at 32% lower force than the Tectonus HD.



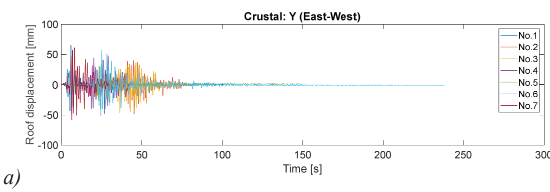
a)



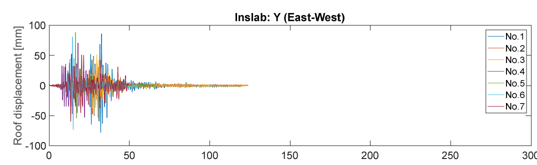
b)

Figure 6: *Comparison of two building models at design intensity level: a) drift, b) HD hysteresis*

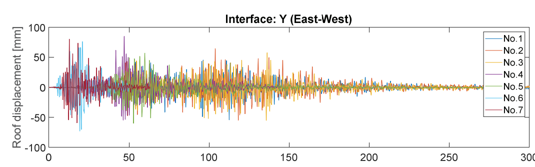
For illustration, roof displacement time histories in the short direction of the building with Tectonus HD are presented in Figure 7, are categorized for each earthquake type. The average of the maximum roof displacements for the long and short directions were 24 mm and 64 mm, respectively, where the maximum displacement of 89 mm was observed from one subduction inslab motion – the Michoacan motion in the short direction.



a)



b)



c)

Figure 7: *Roof displacement time histories in the short direction of the building model with Tectonus HD: a) crustal, b) subduction inslab, c) subduction interface*

Hysteresis curves of the Tectonus building model and representative connections subjected to the Michoacan subduction inslab motion (No. 4 at 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 that the horizontal panel-to-panel spline connection was the primary source for energy dissipation.

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The spline connections in both directions of the building showed large relative displacements and dissipated large amount of the energy. This was followed by the Tectonus HD. The rocking behaviour for this design level shaking resulted in 2 mm uplift and almost 400 kN tension force. The vertical floor-to-floor half-lap connections were capacity protected, and therefor showed almost linear behaviour.

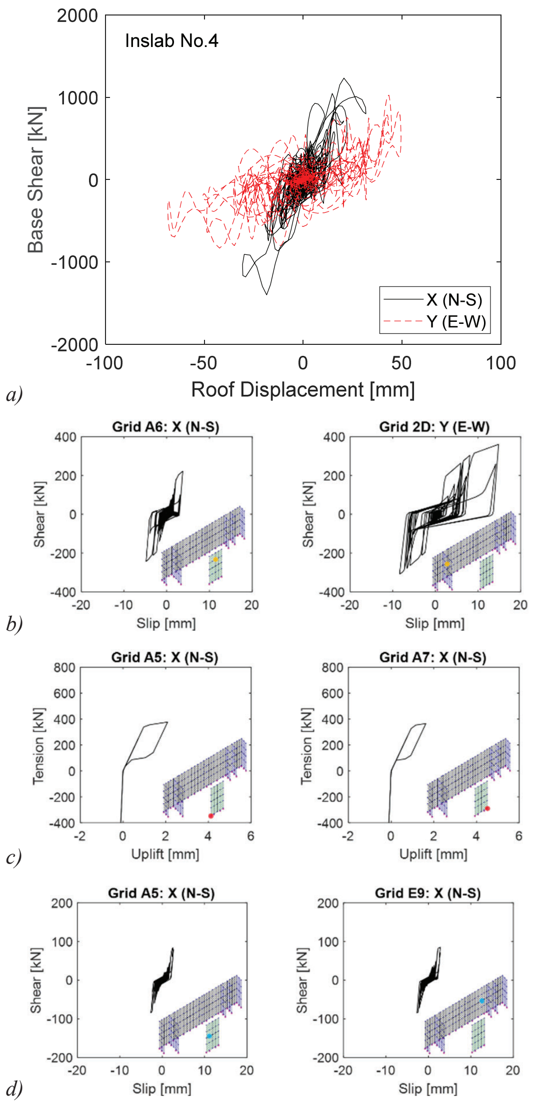

Figure 8: *Nonlinear hysteresis curves during subduction inslab motion: a) global curve, b) horizontal panel-to-panel spline joint, c) Tectonus HD, and d) vertical floor-to-floor half-lap joint*

5 CONCLUSIONS

In this study, a 3D finite element model for a balloon-framed CLT building was developed and calibrated with test data. The building was equipped with a resilient friction-based self-centering device as HD – the first in Canada. For comparison, a second building model designed with conventional dowel-type HD was also developed. The SelfCentering and Pinching4 material models in OpenSees were used for modelling the connections. Twenty-one pairs of ground motion records were selected based on the seismic hazard of the building site for the nonlinear time history analysis. Based on the analysis results, both building models met the drift limit of 2.5% specified in NBCC at the design level. The model with the Tectonus HD showed lower drift compared to the traditional one. Further studies on the collapse capacity and damage fragility of the building model will be conducted to have a comprehensive understanding of the effectiveness of the Tectonus HD for seismic resilience design.

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