Tall Timber Buildings: Innovative Building Design and Damping Considerations

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Abstract

The current trend in tall timber building design is a testament to the need for innovative structural systems. In this paper, a new, coupled cross-laminated timber (CLT) system is illustrated. The CLT wall systems are equipped with energy dissipation systems, and the continuous medium method (CMM) design principle is used. The CMM is a simplified (approximate) elastic method that can be used to analyze and design the preliminary geometries of coupled wall systems for uniform or quasi-uniform structures. The energy dissipation components of the structure are coupling beams between the CLT walls, and an energy-dissipating buckling restrained-brace (BRB) hold-down. Performance of the structure was evaluated using incremental dynamic analysis.

Keywords: Buckling-Restrained Bracing, Coupled Wall Systems, Cross-Laminated Timber, Glued Laminated Timber

Introduction

With the recent introduction of manufactured mass timber elements, such as large-scale engineered cross-laminated timber (CLT) panels, laminated-veneer lumber (LVL), and glued laminated timber (glulam) members, sustainable tall timber buildings have become a viable option (Cover 2020, Ramage et al. 2017). What constitutes a tall timber building is relative to the time, and the definition of tallness in mass-timber buildings is evolving (Foster, Ramage & Reynolds 2017).

A decision on the selection of tall building structures and technology should consider economics, aesthetics, technology, regulations, and political factors (Ali & Moon 2007). In Canada, for example, the political factors include the fact that the Canadian timber industry and Natural Resources Canada are backing design and construction of tall timber buildings. Several Canadian provinces have adopted initiatives to create a "Culture of Wood Use" in public buildings. With this initiative, the 18-story Brock Commons Tallwood House (see Figure 1) and 13-story Origine (Dubois, Frappier & Gallagher 2020) (see Figure 2) buildings were constructed in the city of Vancouver and Québec City, respectively. To date, mass timber buildings up to 12 and 18 stories, respectively, are codified in the 2020 Canadian building code and 2021 International Building Code (Cover 2020).

Under severe earthquake load, through controlled plastic hinge formation and damage, safety at the ultimate limit state is ensured. Timber-only structural members, however, might not be sufficient to meet the demand, as the load-carrying and ductility capacities can be exceeded (Ramage et al. 2017). In addition, excessive damage can impact the post-earthquake functionality and resiliency of the building. Considering hybrid and innovative building systems, this limitation can be overcome. The hybridization can be at the component level (hybrid slab/diaphragms, hybrid beams, hybrid columns, hybrid diagonals, hybrid shear walls) and/or at the system level (hybrid shear wall system, tube system, vertical mixed system).

The author's team recently completed research at the University of British Columbia, supported through Forestry Innovation Investment (FII) and Natural Sciences and Engineering Research Council (NSERC) grants. Two structural systems, considering 10, 15, and 20 stories, were investigated: CLT walls coupled with a replaceable link (Tesfamariam, Skandalos & Teweldebrhan 2021) and CLT core with outrigger beams. In this paper, salient features of the 20-story CLT walls coupled

"The most important sources of intrinsic damping for tall buildings are soil structure interaction (SSI) and structural behavior."

Figure 1. Brock Commons Tallwood House, University of British Columbia, Vancouver, 18 stories, 2017, under construction at left, and completed at right, uses a reinforced-concrete core and timber gravity-resisting system. © Brudder, courtesy of naturallywood.com

Figure 2. Origine, Quebec City, Canada, under construction at left, and completed at right, uses 12 stories of mass timber on top of a one-story concrete podium. © Nordic Structures/Stephane Groleau

with replaceable links are discussed. Damping is one critical factor affecting the design and response of tall timber buildings. The state of the art in damping for tall timber building is also discussed.

Coupled-Wall Timber Buildings: Energy-Dissipating Coupling Beams

The 20-story building has a 33-by-33-meter plan dimension. Figure 3a shows detail of the gravity load-resisting system, CLT floors, and glulam columns. The lateral resisting system entails two equal CLT wall widths (6 meters' length each in the Y direction) and two unequal CLT walls (2.5 and 5.5 meters' length each, in the X direction). As the CLT walls are continuous, considered as balloon-type, based on the CLT panel manufacturing height limits, couplers can be used (see Figure 3b). This type of coupler was used on the aforementioned Origine building (Dubois, Frappier & Gallagher 2020).

Details of the lateral load-resisting CLT wall system, for the Y direction, follow here. For the two 6-meter CLT wall systems, two 3-meter CLT walls are coupled with energy dissipation connectors (results shown in this paper are for a rigid connection). In addition, buckling-restrained brace (BRB) hold-downs, at the ends of the six-meter CLT wall, are used (see Figure 3e). As the CLT-wall length increases beyond six meters, additional couplers and CLT panels can be added. Besides the BRB hold-down, the novelty of

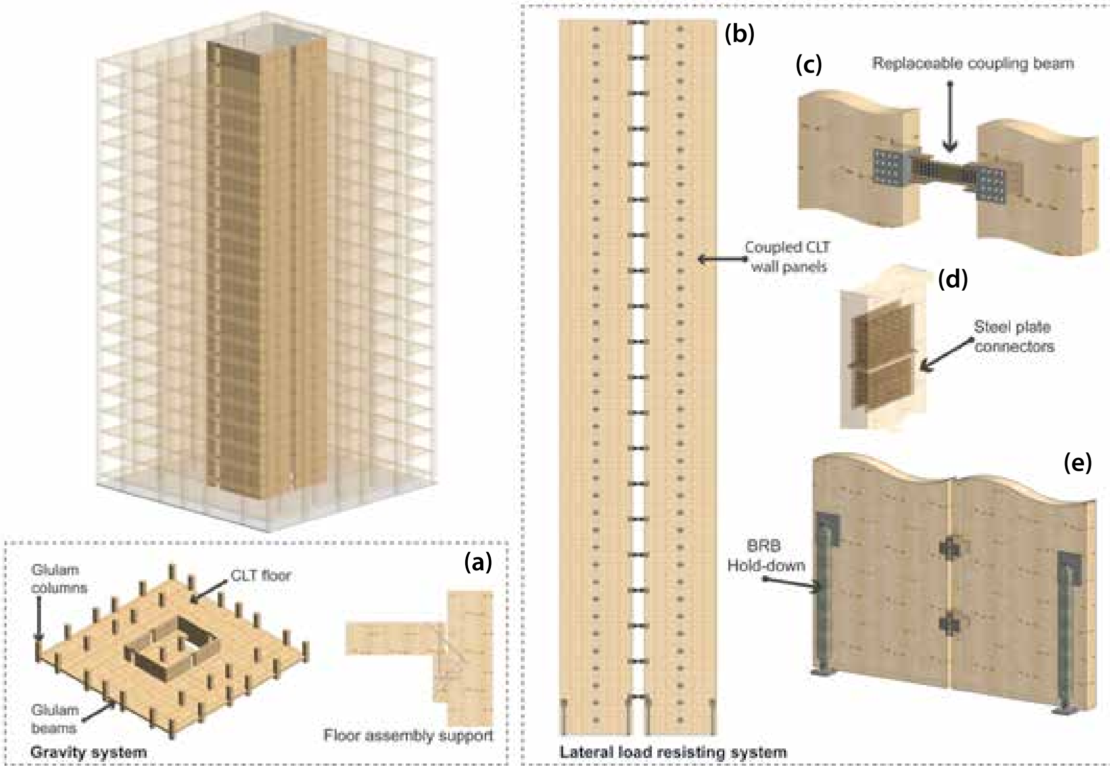

Figure 3. Tall timber coupled-wall building model, showing details of gravity system, energy dissipation coupling beams, and hold-downs.

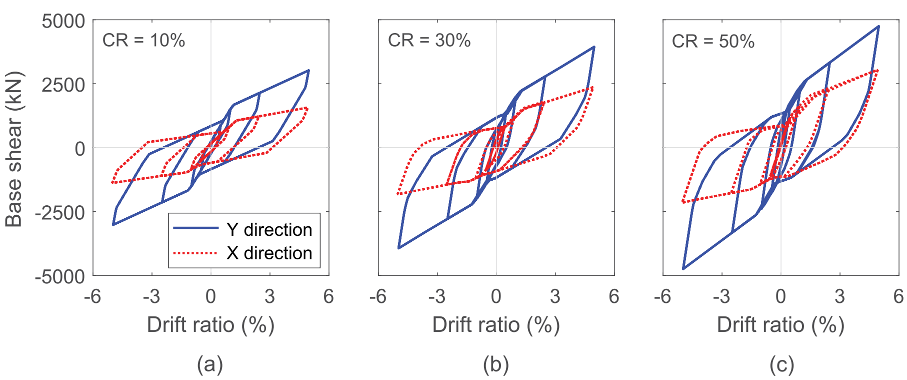

Figure 4. Reverse-cyclic pushover analysis results in the X direction (unequal length wall) and Y direction (equal-length wall) for three coupling ratios (CRs): a) 10, b) 30, and c) 50 percent.

the proposed structural system is in introducing a coupled wall (CW) system design, using a replaceable-link coupling beam between the two 6-meter coupled CLT walls (see Figure 3c). Thus, multiple energy dissipation mechanisms are provided. The building was designed for Vancouver, Canada, a high seismic region.

Performance-Based Design

Different national and international seismic design codes follow prescriptive (deterministic) and force-based design (FBD). The seismic design principles are for first-mode deformation response and collapse prevention limit state. This is not suitable for tall-timber buildings that have higher mode contributions (Ramage et al. 2017). For tall timber and hybrid systems that are outside of the code-oriented practice, performance-based design (PBD) is a viable approach. The PBD evaluation entails consideration of site-specific seismic hazard assessment, and selecting ground motions and performance assessment using NRHA.

The CW system design principles (Tesfamariam, Skandalos & Teweldebrhan 2021) were adopted for the proposed tall timber building. Continuous Medium Method (CMM), a simplified (approximate) elastic method that can be used to analyze and design the preliminary geometries of CW systems, was adopted. The method reduces the statically indeterminate CW system into a problem modeled as a single fourth-order differential equation, and furnishes closed-form solutions, depending on the type of lateral loads. The steps followed in the design are:

- Step 1. Calculate seismic forces and overturning moment using equivalent lateral force analysis (ELFA)
- Step 2. Calculate the equivalent uniformly varying load

- Step 3. Apply CMM and calculate its parameters
- Step 4. Calculate the force parameters in the CW system
- Step 5. Design the CLT-CW structural elements
- Step 6. Design coupling-beam-to-CLT and hold-down-to-CLT connections
- Step 7. Model the system and validate the design through pushover analysis and nonlinear response history analysis (NRHA).

Details of the steps and design examples are provided in Tesfamariam, Skandalos & Teweldebrhan (2021). The 20-story building was designed for different coupling ratios (CRs) – 10, 30, and 50 percent. Reverse-cyclic pushover analysis responses for the three CRs, in the X and Y directions, are shown in Figure 4. From the cyclic pushover analysis results, the following observations can be made:

- The system has a non-degrading energy dissipation mechanism
- The unequal coupled CLT wall system is weaker, and can govern the design of the building
- With an increase in CR, i.e., from 10 to 50, the base shear capacity of the system increases.

Vancouver, Canada, is subject to crustal, inslab, and interface earthquakes. The inslab earthquake, in particular, has a long-period ground motion record, and can be critical for tall timber buildings. Using probabilistic seismic hazard models for southwestern British Columbia, 30 bidirectional ground motion (GM) records are selected. Maximum considered earthquake record (MCER) for Canadian code is 2 percent probability of exceedance in 50 years (i.e., 2,500 years return period).

Nonlinear Response History and Fragility Analyses

The NRHA was carried out using incremental dynamic analysis (Vamvastikos & Cornell 2001), scaling the GM records to reach collapse limit state. The input ground motion record for GM=1 at MCE_R is shown in Figure 5a. The non-linear response, interstory drift ratio (Figure 5b), floor acceleration (Figure 5c), and force/displacement response of the replaceable link coupling beams (Figure 5d), are also shown. Figure 6 shows the nonlinear response of the hold-down. From the results in figures 5 and 6, it is worth noting that, with increase in CR, the force demand on the replaceable link-coupling beam is increasing, and corresponding displacement demand on the hold-downs is decreasing. Optimal design configuration can be achieved by controlling the CR and hold-down strength.

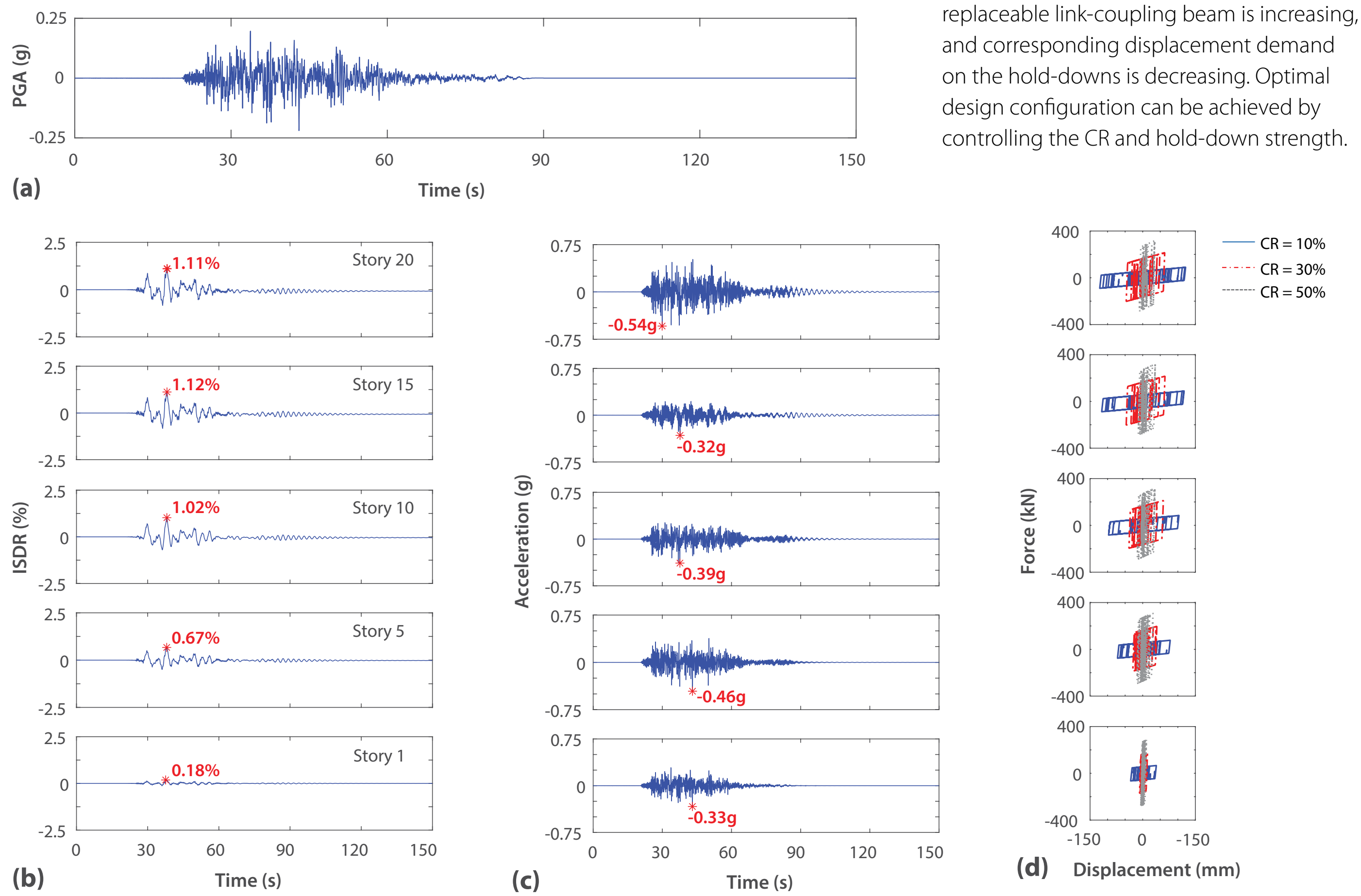

Figure 5. Ground motion inputs and corresponding interstory drift ratio (ISDR), floor acceleration, and force-displacement of the replaceable coupling link in the Y direction for CR = 10, 30, and 50 percent.

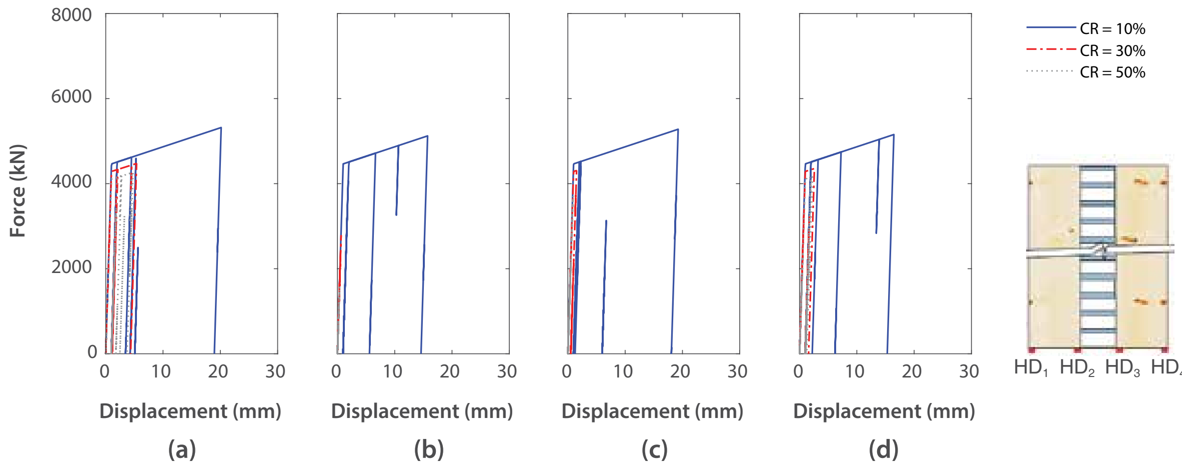

Figure 6. For ground motion (GM) one record, hold-down responses in the Y direction for CR = 10, 30, 50 percent: a) HD_1, b) HD_2, c) HD_3, and d) HD_4.

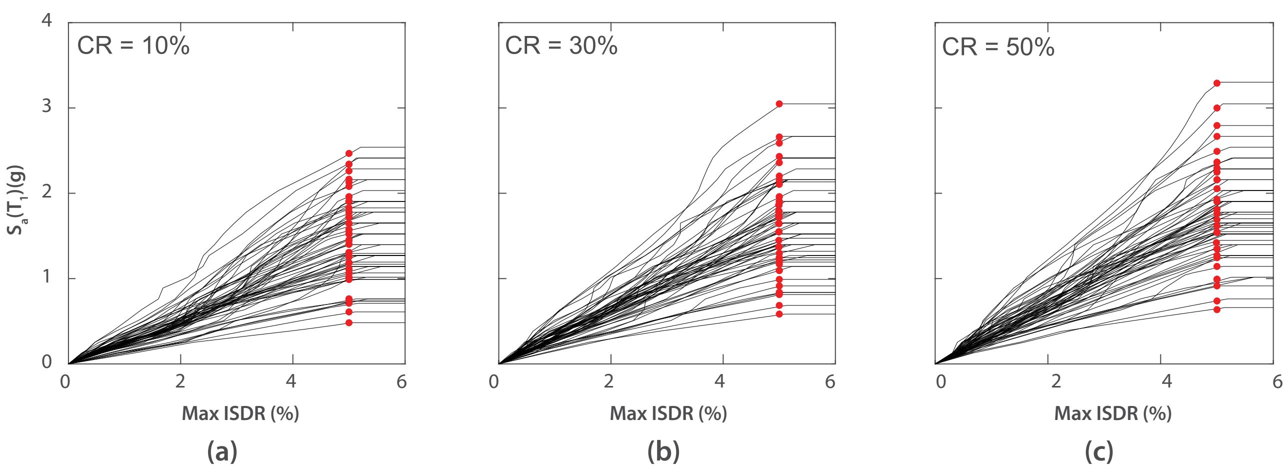

Figure 7. Incremental dynamic analysis results for maximum interstory drift ratio (MaxISDR) and $S_a(T_1)$ at CR= a) 10, b) 30, and c) 50 percent.

For all GMs, results of the IDA for the Y-direction, with CR = 10, 30, and 50 percent, are shown in Figure 7.

The IDA results depicted in Figure 7 are used to compute the collapse and non-collapse fragility curves. The intensity measure used in the seismic analysis is the spectral acceleration (S_a) at the first mode period (T_1), denoted as $S_a(T_1)$. The probabilistic seismic demand model, $D = a \cdot S_a(T_1)^b$ is used to compute the demand at a given $S_a(T_1)$. The fragility, the probability of D exceeding C at $S_a(T_1)$, $P(D > C \mid S_a(T_1))$, can then be computed as:

$$P(D > C|S_a(T_1)) = 1 - \Phi\left(\frac{\ln(\hat{C}) - \ln(a \cdot S_a(T_1)^b)}{\sqrt{\beta^2_{D|S_a(T_1)} + \beta^2_C + \beta^2_M}}\right)$$

where $\hat{C}$ is median structural capacity associated with the limit state; a and b are regression coefficients for the probability seismic demand models, and $\beta_C = 0.2$ and $\beta_M = 0.2$ capture the aleatoric uncertainty in capacity C and epistemic uncertainty in modeling, respectively.

The relationships between different earthquake return periods and acceptable performance limit states are shown in Table 1. The structural response limit state in the NBC (2020) is maximum inter-story drift ratio (Max ISDR). For frequent (50 years return period), occasional (100 years return period), rare (500 years return period), and very rare (2,500 years return period) earthquake levels, the basic objective limit states are Immediate Occupancy (IO, Max ISDR = 0.5 percent), Damage Control (DC, Max ISDR = 0.5 percent), Life Safety (LS, Max ISDR = 1.5 percent), and Collapse Prevention (CP, Max ISDR = 2.5 percent), respectively. For the proposed system, Max ISDR = 5.0 percent was considered as the collapse limit (red dots in Figure 7). With the consideration of IO, LS, and CP limit states, the fragility curves are computed and depicted in Figure 8. In addition, the collapse points in Figure 7 (red dots), a lognormal distribution was applied, and the corresponding collapse fragility is

Earthquake design level (probability of exceedance = PE)	Performance limit states			
	Immediate Occupancy (IO)	Damage Control (DC)	Life Safety (LS)	Collapse Prevention (CP)
Frequent (50% PE in 30 years)	■	×	×	×
Occasional (50% PE in 50 years)	◆	■	×	×
Rare (10% PE in 50 years)	◊	◆	■	×
Very rare (2% PE in 50 years)		◊	◆	■

■ Basic objective – Proposed NBC normal importance

◆ Essential service objective – Proposed NBC high importance

◊ Safety critical objective – Not proposed NBC category

× Unacceptable performance for new construction

Table 1. Vision 2000 recommended seismic performance objectives for buildings. Source: SEAOC 1995.

shown in Figure 9. From the fragility analysis, the following results are highlighted:

- For non-collapse limit state, the effect of CR on the Y and X directions show appreciable difference. Consistent with the non-collapse limit states, the probability of exceedance for CR = 50 percent is lower. In addition, the difference in fragility curves for CR = 10, 30, and 50 percent increases from IO to CP limit states.
- For collapse limit state, the effect of CR on the Y direction shows appreciable difference. Consistent with the non-collapse limit states, the probability of exceedance for CR = 50 percent is lower.
- For collapse fragility, the effect of the CR on the X direction fragility diminishes.

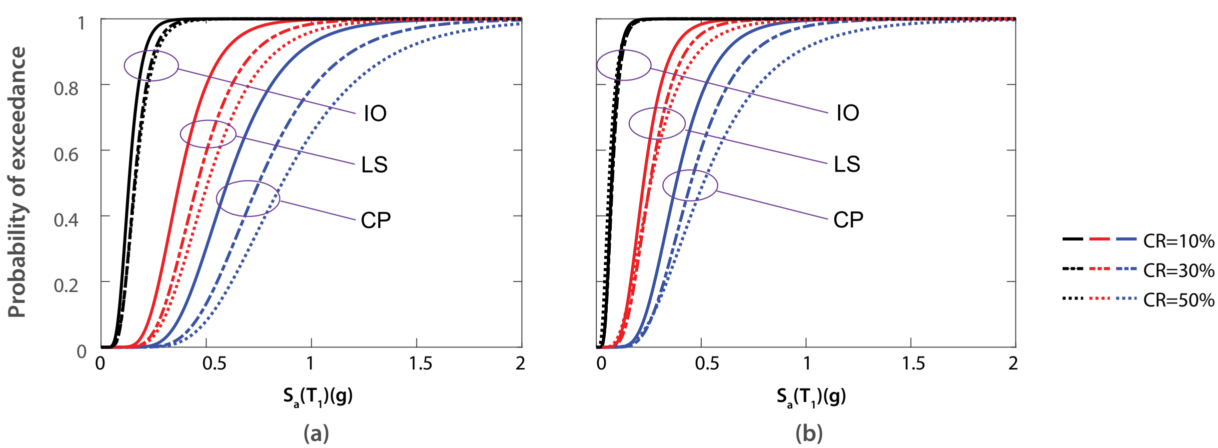

Figure 8. Non-collapse fragilities for CRs of 10, 30, and 50 percent in the a) X and b) Y directions.

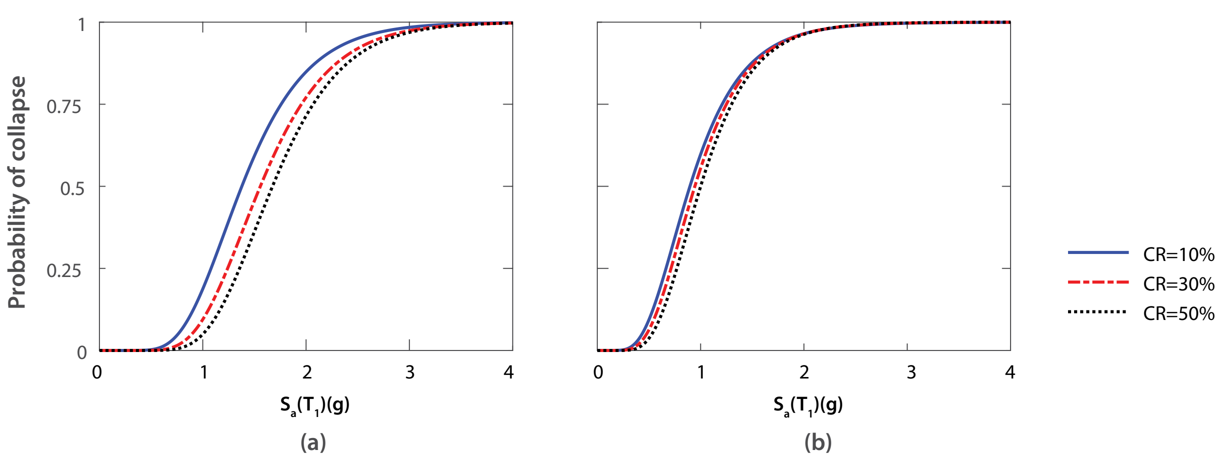

Figure 9. Collapse fragilities for CRs of 10, 30, and 50 percent in the a) X and b) Y directions.

Damping

Sources of damping in tall buildings are intrinsic/inherent (or structural), aerodynamic, hysteretic, and supplemental/additional (Lago, Trabucco & Wood 2018; Smith, Merello & Willford 2010). Factors that contribute to the damping include: material, friction between members and connections, structural system and joint types, foundation and soil types, interior partitions, exterior cladding, other non-structural members, and vibration amplitude (Lago, Trabucco & Wood 2018). Intrinsic damping is related to energy dissipation of the structural system that increases (nonlinearly) with amplitude and decreases with natural frequency (Tamura & Suganuma 1996). The most important sources of intrinsic damping for tall buildings are soil structure interaction (SSI) (Cruz & Miranda 2021) and structural behavior. Within the limited typology of tall timber buildings, the damping associated with structural systems is not readily available for design. Aerodynamic damping is related to dynamic interaction of air and building movement (Kareem & Gurley 1996). This damping is often neglected for typical tall buildings (Lago, Trabucco & Wood 2018); however, it can be relevant with more advanced tall timber buildings designed recently (Ramage et al. 2017). Hysteretic damping is the energy dissipation resulting from the inelastic behavior of structural elements activated under severe loading conditions (e.g., earthquake) (Cruz & Miranda 2021) and is associated with permanent damage to the structure (Smith, Merello & Willford 2010). As the hysteretic damping is implicitly incorporated through nonlinear modeling, the lower damping values recommended for wind should be considered (Smith, Merello & Willford 2010; Willford et al. 2008). Supplemental damping is associated with devices added to the building system (Lago, Trabucco & Wood 2018).

The damping associated with different mass timber building typologies and connections can be quantified from field measurement (Smith, Merello & Willford 2010). With *in situ* ambient vibration measurements Edskär & Lidelöw (2019) and Reynolds et al. (2016) reported on the building height to damping relationship (see Figure 10). Here, it is apparent that, as expected, with increase in building height, the damping values are decreasing. There is variability in the damping values obtained for the timber buildings. The damping-height empirical equations for steel, concrete, and steel-concrete buildings, reported in Smith, Merello & Willford (2010), are plotted in Figure 10. Overall, both show a similar trend, and some of the damping values for the timber buildings are bounded between the steel and reinforced-concrete (RC) damping-to-height relationships. The current analytical studies reported on mass timber buildings do not consider the SSI. Thus, the response obtained through *in situ* measurements and analytical studies can be different (Edskär & Lidelöw 2019). Future analytical studies should incorporate the SSI in the damping calculations.

Conclusions

In this paper, recent innovative systems introduced by the author at the University of British Columbia, supported through FII and

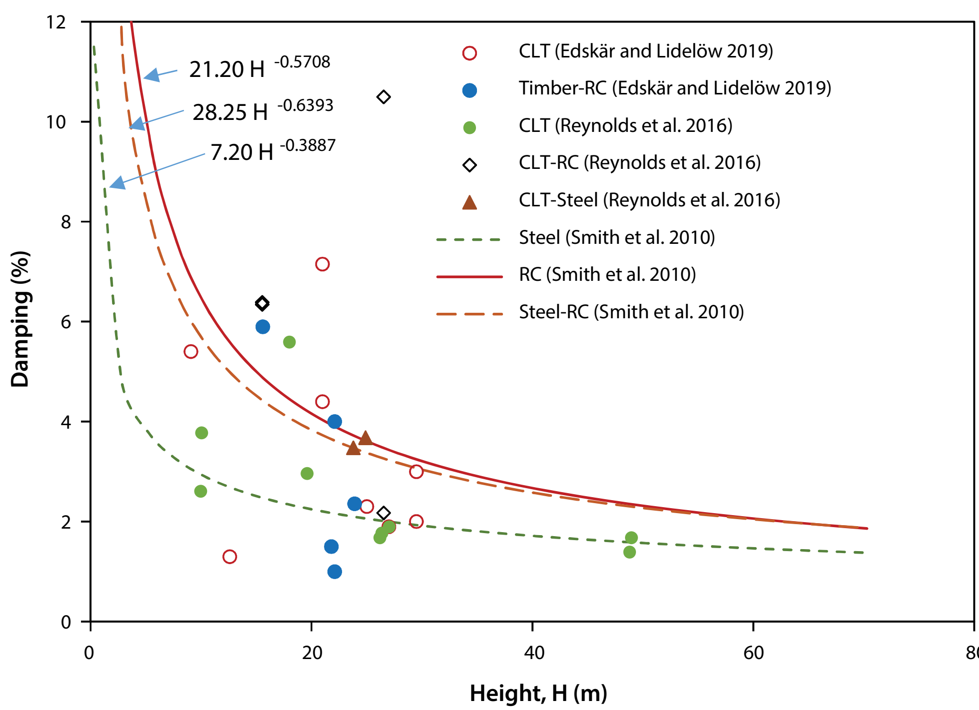

Figure 10. Empirical equations showing the relationship of height to level of damping, based on the given structural systems.

NSERC grants, were described. One of the innovative systems expounded in this paper entails CLT wall systems coupled with replaceable links (Tesfamariam, Skandalos & Teweldebrhan 2021). This structural system has well-defined energy dissipation mechanisms. In post-earthquake severe damage, the BRB hold-down and replaceable links contribute to the energy dissipation. Indeed, the salient feature of the CLT wall systems entails replacing those damaged links and reducing the downtime and resiliency of the building. The CMM design principle used was easily implemented in a simple spreadsheet. The proposed system is promising, in that it successfully meets different performance levels, and has a well-defined energy-dissipation mechanism.

Damping, however, is a critical factor affecting the design and response of tall timber buildings, and thus should be an area of ongoing research. The state of the art in modeling damping for tall timber building has been discussed here. SSI, an important factor in the damping, is not often considered in the analysis and design of tall timber structures. This can over- or under-estimate the response, and it is prudent to consider in future studies. In addition, the innovative design and implementation of supplementary damping and topology optimization, for tall timber buildings, is an area the author is currently working on. ■

“Besides the BRB hold-down, the novelty of the proposed structural system is in introducing a coupled wall (CW) system design, using a replaceable-link coupling beam between the two 6-meter coupled CLT walls.”

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