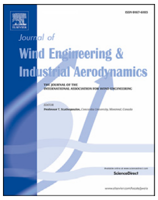
Journal of Wind Engineering & Industrial Aerodynamics 181 (2018) 85–103

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia



Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part I - structural design and wind tunnel testing

M.A. Bezabeh [a,b], G.T. Bitsuamlak [a,*], M. Popovski [c], S. Tesfamariam [b]

[a] *Department of Civil and Environmental Engineering, Western University, Canada*
[b] *School of Engineering, University of British Columbia, 3333 University Way, Kelowna, BC, V1V 1V7, Canada*
[c] *FPInnovations and University of British Columbia, Canada*

ARTICLE INFO

Keywords:
Tall mass-timber buildings
Wind tunnel testing
Performance-based wind engineering
Design of tall mass-timber building
Wind load
Drift

ABSTRACT

Tall mass-timber buildings utilize engineered wood panels to form their main gravity and lateral load resisting systems, which makes them lighter and very flexible. As a result, frequent exposure to excessive wind-induced vibrations can cause occupant discomfort and unserviceability due to horizontal floor acceleration and excessive deflection. Therefore, the objective of this and the companion paper is to assess the serviceability performance of tall mass-timber buildings probabilistically. For this purpose, the Alan G. Davenport Wind Loading Chain is adapted as a probabilistic Performance-Based Wind Engineering framework. The framework is applied to quantify the serviceability performance of a 102-m tall mass-timber building. In this paper, a complete tall-mass timber building structural design process is outlined. Wind loads are obtained from aerodynamic wind tunnel tests conducted at the Boundary Layer Wind Tunnel Laboratory at Western University. The design process involves preliminary strength design using the provisions of building codes, design revisions using wind load from wind tunnel tests, and serviceability checks. The structural design of the case study tall mass-timber building considers the axial compression, in-plane-shear, and in-plane and out-of-plane bending moment demands, along with their interactions due to gravity and wind loads. Dynamic analysis is carried out to assess the drift performance of the case study mass-timber building. The results show that the building satisfies the drift requirements prescribed by the building codes with a small safety margin. For the designed tall mass-timber building, an in-depth probabilistic serviceability-performance assessment and vulnerability estimations are presented in the companion paper.

1. Introduction

The rapid growth of urban population and the associated environmental concerns are partly influencing city planners and construction stakeholders to consider “Sustainable Urbanization” alternatives. The sustainable urbanization has emerged as a viable solution towards smart and livable cities which are more resilient, and environmental friendly (Green and Karsh, 2012; Karacabeyli and Lum, 2014). To achieve this goal, recent urban design strategies are entertaining the use of “tall timber buildings”. In 2015, the National Building Code of Canada raised the height limits on light wood-frame construction from four to six stories. Even though wood-frame construction is limited to 6-stories, mass-timber buildings can go taller. Usually, mass-timber buildings utilize pre-engineered wood panels such as Cross Laminated Timber (CLT) as the main construction material. CLT is a lightweight pre-engineered panel made by gluing lumber boards in alternate directions. Due to superior dimensional stability and load carrying capacity, the main gravity and lateral load resting systems of tall mass-timber buildings can be constructed using CLT panels. Over the past 15 years, with the use of CLT panels, several tall timber-based buildings were constructed. Table 1 lists nine constructed tall timber-based buildings in different countries.

In 2017, the University of British Columbia (UBC) finalized the construction of 18 stories (53 m) tall hybrid mass-timber residential building. Currently, the building is the tallest standing timber-based building in the world, where the top 17 floors of the building were constructed using CLT. Glulam columns were used to transfer the gravity load to the foundation, while two reinforced concrete (RC) cores resist wind and earthquake loads. The success of existing timber-based buildings in

---

* Corresponding author.

E-mail addresses: matiyas.bezabeh@alumni.ubc.ca, mbezabeh@uwo.ca (M.A. Bezabeh), gbitsuam@uwo.ca (G.T. Bitsuamlak), marjan.popovski@fpinnovations.ca (M. Popovski), Solomon.Tesfamariam@ubc.ca (S. Tesfamariam).

https://doi.org/10.1016/j.jweia.2018.08.012
Received 19 February 2018; Received in revised form 17 August 2018; Accepted 23 August 2018

meeting their design objectives enhances the confidence of architects and developers towards pushing the height limits of timber buildings beyond 50 m. To name a few examples, Skidmore, Owings and Merrill (SOM LLP) designed a 42-story hybrid tall-mass timber apartment building based on a benchmark building in Chicago USA (SOM, 2013). In Canada, Michael Green and Eric Karsh proposed a 30-story hybrid tall mass-timber building known as "Finding the Forest through the Trees (FFTT)" (Green and Karsh, 2012). Chen and Chui (2017) applied the results of collaborative research between NEWBuilds and FPinnovations to design a 20-story hybrid mass-timber building. Recently Arup Group Limited proposed a 21-story tall timber building in Amstelkwartier, Netherland (Arup, 2017). Trätoppen, a 40-story timber building, is proposed by Anders Berensson Architects to be built in Stockholm (Anders Berensson Architects, 2017). CallisonRTKL performed the design and feasibility study of a 40-story "Seattle mass-timber" tower (CallisonRTKL, 2017). Department of Architecture at Cambridge University, PLP Architecture, and Smith and Wallwork conceptually designed a 300 m high-rise timber building in London, England (Ramage et al., 2017).

Overall, research on timber structures is gaining momentum to develop wooden skyscrapers. For example, in Canada, FPInnovations released the first comprehensive design and construction guide for tall timber buildings (Karacabeyli and Lum, 2014). Researchers at the University of British Columbia and FPInnovations also developed both force- and displacement-based design guidelines for timber-steel hybrid system (Tesfamariam et al., 2015; Bezabeh et al. 2016, 2017). In the USA, "NHERI Tall wood Project" was launched in 2016 to develop a resilience-based seismic design guideline for tall timber buildings (Pei et al., 2017). This collaborative research is aimed at quantifying the seismic resilience of tall wood buildings through mechanistic models validated by full-scale shaking table tests. In addition, in the past few decades considerable research has been carried out on the wind performance of low-rise wood buildings, (Guha and Kopp, 2014, Zisis and Stathopoulos, 2012, Zisis et al., 2011, Morrison and Kopp, 2011, Dao and van de Lindt, 2011, van de Lindt et al., 2007, Li and Ellingwood, 2006, and Rosowsky and Ellingwood, 2002, Liu et al., 1990, Sparks et al., 1988). While most of the studies focused on material science, fire, and seismic performance evaluations, wind performance of high-rise timber buildings has scarcely been studied. Tall mass-timber buildings tend to be lightweight and more flexible than buildings made of steel, concrete or masonry. The increased flexibility limits the lateral stiffness, thus making mass-timber buildings vulnerable to excessive along- and across-wind vibrations (Reynolds et al., 2011; Popovski et al., 2014; Fairhurst, 2014; Feldmann et al., 2016; Bezabeh et al., 2018). As a result, frequent exposure to excessive wind-induced vibrations can cause occupant discomfort and possible inhabitability and unserviceability of this kind of emerging buildings. Therefore, in this and companion paper (Bezabeh et al., 2018b), a performance-based wind engineering (PBWE) framework is applied to probabilistically assess the serviceability-performance of tall mass-timber buildings based on the aerodynamic information from the wind tunnel tests.

2. Probabilistic performance-based wind engineering: conceptual considerations

Current prescriptive building design approaches consider designing for a single limit state by accounting uncertainties through safety coefficients to achieve safety and acceptable serviceability levels. Efforts to improve designs for a fixed limit state started decades ago in the earthquake engineering community after an enormous amount of monetary losses due to the 1989 Loma Prieta and 1994 Northridge Earthquakes in California. Performance-based engineering considers a range of limit states (performances objectives) throughout the lifetime of the structures to make risk-based decisions. In wind engineering, suggestions to design structures for different limit states was first introduced by Davenport and Hill-Carroll (1986). The identified limit states in Davenport and Hill-Carroll (1986) are ultimate strength, permanent deformation, excessive acceleration (occupant discomfort), and integrity of cladding and finishing materials.

Table 1
Summary of constructed tall timber based buildings (Bowyer et al., 2016).

Building	Country	Completion date	No. of stories
Limnologen	Sweden	2009	8
Bridport -House	England	2010	8
Hlz8	Germany	2011	8
Forte	Australia	2011	10
Life Cycle- Tower One	Austria	2012	8
Pentagon II	Norway	2013	8
Treet	Norway	2016	14
UBC Tall Wood Building	Canada	2017	18
T3, Minneapolis	USA	2017	7

Performance-based engineering requires accurate models of hazard, hazard-structure interaction, structural properties, criteria, and consequences. In 1961, the late Alan G. Davenport introduced a mathematical, somewhat philosophical, model to evaluate wind loads on structures similar to the current context of performance-based engineering (Davenport, 1961a,b, 1977, 1983). He coined his thought process as interconnected chains and named the performance evaluation framework as "*Wind Loading Chain*" (Davenport, 1982). Davenport's *Wind Loading Chain* laid the foundation for modern wind engineering and provides a theoretical basis for many buildings codes and standards. In 2011, the International Association of Wind Engineering (IAWE) recognized the *Alan G. Davenport Wind Loading Chain* as an official wind engineering terminology (Isyumov, 2012). For performance assessment and design of structures, the Wind Loading Chain (Fig. 1) starts by modeling the local micro-climate of a target site to predict the design wind speeds. Statistical analysis of historical wind speed data or computer simulations can be used to determine the design wind speeds (Davenport, 1961a,b; Isyumov et al., 2014; Harris and Cook, 2014; Zhang and Chen, 2015). The approaching wind flow around the building site is affected by the terrain roughness and local topography. These effects are accounted for through the second element of the Wind Loading Chain. Building aerodynamics (or simply, building shape effects) is another factor that significantly affects the wind loads and response of structures. Wind tunnel tests and computational fluid dynamics can be used to study bluff body aerodynamics (Davenport and Isyumov, 1967; Isyumov, 1972; Stathopoulos, 1984; Isyumov et al., 1992; Irwin, 2008; Bitsuamlak and Simiu, 2010; Irwin et al., 2013; Dagnew and Bitsuamlak, 2013, 2014; Blocken, 2014; Aboshosha et al., 2015). Davenport (1967) developed a framework to quantify the dynamic response of structures to wind using random vibration theory. In the framework, he suggested an approach to linearize the dynamic wind force equation and to perform dynamic analysis under wind load in the frequency domain. Finally, the performance of the structure could be judged by comparing the peak response demands with criteria from building codes and standards.

To extend the *Alan G. Davenport Wind Loading Chain* towards Performance Based Wind Engineering (PBWE) framework, a collaborative research is currently underway between UBC, Western University, and FPInnovations. The research program includes several wind tunnel tests on tall mass-timber building models subjected to both synoptic and non-synoptic (tornadic) wind loads. Different performance and damage limit states are being developed using both linear and non-linear aeroelastic wind tunnel tests. Part of the collaborative research, i.e., serviceability wind performance assessment of tall mass-timber buildings using the *Alan G. Davenport Wind Loading Chain* as a PBWE framework is presented in this and the companion paper (Bezabeh et al., 2018b).

3. Application of probabilistic PBWE for tall mass-timber buildings

In this and the companion paper, the *Alan G. Davenport Wind Loading Chain* is revisited and adapted as a probabilistic PBWE framework for