Engineering Structures 177 (2018) 519–539

Contents lists available at ScienceDirect

Engineering Structures

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

Structural performance of multi-story mass-timber buildings under tornado-like wind field

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ARTICLE INFO

Keywords:
Mass-timber buildings
Structural performance
Tornado-like wind field
Enhanced Fujita
Boundary layer flow

ABSTRACT

Tall mass-timber buildings utilize engineered wood panels to form their main gravity and lateral load resisting systems, which makes them lighter and more flexible than buildings made from concrete, masonry or even steel. In general, drift sensitive components of tall mass-timber buildings could be susceptible to damages due to increased deflection when subjected to extreme wind storms like violent tornadoes. This paper assessed the structural performance of a multi-story mass-timber building, which was designed using the customary 1-in-50 years design wind speed of the *2010 National Building Code of Canada* with a load factor of 1.4, under experimentally simulated tornado-like wind fields. In the study, wind loads were obtained from laboratory simulations of tornado-like wind field and atmospheric boundary layer flow at Western University, Canada. Tornadic wind loads from the laboratory tests were scaled to five Enhanced Fujita wind speeds, representing various levels of damage. Dynamic structural analyses were carried out in time-domain to include the possible amplification due to the dynamic component of the excitation and assess floor level inter-story drift and shear force demands for various parameters. The varied parameters were tornado intensity level, the orientation of the building (aerodynamic direction), and critical damping ratio. Based on the obtained results, the vulnerability of drift sensitive components of the study building under tornado-like wind field was estimated. It is shown that strong tornadoes may pose significant damage to drift sensitive non-structural components of multi-story mass-timber buildings. Finally, roadmaps to improve the design of mass-timber buildings in tornado-prone areas are forwarded.

1. Introduction

1.1. Tall mass-timber buildings

Properly designed urban densification can reduce suburban sprawl, provide chances for better public transportation, promote interconnected society, and provide opportunities for commercial, cultural, and intellectual interactions. The rapid growth of world's urban population and the associated environmental concerns are partly influencing the consideration of "sustainable urbanization" alternatives. In recent years, sustainable urbanization has become a viable solution towards high-density, smart, resilient, and habitable cities through the construction of tall buildings. Studies on the life cycle assessment of building materials and systems indicate that wood is an efficient construction material in terms of embodied energy and greenhouse gas emissions (e.g., [95,34]). To this end, latest design guidelines and standards in US and Canada are considering the use of mass- timber for multi-story buildings (CSA O86-14, NDS 2015). In addition, in the past decade, considerable research has been carried out on the wind performance of low-rise wood-frame structures, to name a few- Zisis and Stathopoulos [99], Zisis et al. [100], Morrison and Kopp [62], van de Lindt and Dao [91], van de Lindt and Dao [90].

Mass-timber buildings most commonly utilize engineered wood panels such as cross-laminated timber (CLT) as main construction material. CLT is a lightweight, pre-engineered panel made by gluing lumber boards in alternate directions. Due to its superior dimensional stability and load carrying capacity, CLT can be used to construct the main gravity and lateral load resisting systems of tall mass-timber

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https://doi.org/10.1016/j.engstruct.2018.07.079
Received 13 April 2018; Received in revised form 5 July 2018; Accepted 25 July 2018
0141-0296/

buildings. The 2015 *American National Design Specification (NDS) for Wood Construction* [3] and the 2016 supplement of the *Canadian National Standard for Engineering Design in Wood (CSA O86)* included chapters dedicated to the design of CLT structural elements. In 2018, the *International Building Code (IBC) Ad Hoc Committee on Tall Wood Buildings* approved the application of "heavy-timber" structural elements for constructions beyond Type IV [6]. In addition to inclusion in the building codes and standards, in Canada, the University of British Columbia (UBC), FPInnovations and the Natural Resources Canada (NRCan) developed design guidelines for timber-hybrid and mass-timber-based buildings [35,40,52,85,12]. In the USA, "NHERI Tall Wood Project" was launched in 2016 to develop a resilience-based seismic design guideline for tall timber buildings [69].

While most of the state-of-the-art studies and design guidelines focused on seismic design and performance evaluations, wind performance of high-rise timber buildings is an emerging area [74,70,31,32,73]. Tall mass-timber buildings tend to be lightweight and more flexible than buildings made of steel, concrete or masonry. Compared to reinforced concrete buildings, the weight reduction due to the use of timber as the main structural material could reach up to 50% [81]. The lightweight and increased flexibility limit the lateral stiffness, thus making mass-timber buildings vulnerable to excessive wind-induced vibrations [74,70,31,32]. Therefore, the lateral strength and stiffness requirements due to wind loads could govern the design of tall mass-timber buildings. In addition, the lightweight nature of mass-timber buildings could make them somewhat susceptible to overturning when subjected to extreme windstorms such as violent tornadoes that can produce a net uplift force greater than the dead weight of the structure. Towards this end, a collaborative research is currently underway between The University of British Columbia, Western University (The Wind Engineering, Energy, Environment, WindEEE Dome, and The Boundary Layer Wind Tunnel Laboratory, BLWTL) and FPInnovations to develop Performance Based Wind Engineering (PBWE) frameworks to design tall mass-timber buildings up to 136 m tall. The research program includes several wind tunnel tests on tall mass-timber building models subjected to both synoptic and non-synoptic (tornadic) wind loads. In this paper, part of this collaborative research, i.e., structural performance assessment of mass-timber buildings subjected to tornado-like wind field is presented. To the best of authors' knowledge, no study has been conducted to assess the performance of such buildings under the action of tornadic winds.

1.2. Tornado damage and risk assessment: a survey

A tornado, sometimes referred to as a twister, is a fast spinning air column that stretches between the clouds and the earth surface. Tornadoes are often regarded as one of the most violent storms in nature and are ranked third, after floods and hurricanes, in the United States, based on total damage and number of fatalities due to natural hazards [24]. The midwestern US experiences the highest frequency of tornadoes every year; commonly referred to as the tornado alley [39]. Tornadoes are rated on the Fujita (F) scale from 0 to 5 based on the extent of damage, with F0 being the least damaging and F5 being the most damaging tornado. While each damage level on the F-scale is associated with a wind speed, the wind speeds were not meticulously verified, causing overestimation in many cases. As a result, the F scale was replaced by Enhanced Fujita (EF) scale in 2007 in the US and in 2013 in Canada. According to Wind Hazard Reduction Coalition, with an average number of 1000 tornadoes every year that cause 1500 injuries, 80 deaths and $850 million in property damage, the US ranks number one in terms of number of tornado occurrences and tornado-related damage in the world [39]. Canada is ranked second in the world with annual average tornado occurrence of 80–100 according to Environment Canada. Similar to some states in Midwestern US, the province of Ontario has experienced some of the deadliest and most destructive tornadoes in Canada. For example, the May 31, 1985, Barrie tornado and the June 17, 1946 Windsor tornadoes killed 12 and 17 people, respectively, with a significant amount of damage to buildings. Alarmed by the damage potential of tornadoes, researchers have turned their focus towards tornado-structure interaction and tornado-induced wind loads on civil structures in the past few decades.

Traditionally, wind engineering researchers have studied the impact of straight-line (ABL) wind on structures using wind tunnel (e.g., [26,88,17,51] and computational (e.g. [25,13,29] approaches. However, the transient, localized and three-dimensional nature of tornadoes makes the resulting aerodynamic wind loading substantially different wind loads arising from conventional Atmospheric Boundary Layer (ABL) flow. As a result, several experimental and computational studies have been conducted to understand the interaction of tornado-like wind field with terrestrial structures (e.g. [80,59,77,45,87,97,78,15,2,58,66,65]. Except for nuclear facilities, the current building codes in Canada and the US do not enforce design for tornado risk due to their low probability of occurrence and the economics of the owner.

Banik et al. [8] reported that southern Ontario has a low probability of a tornado hazard exceeding the factored design wind load of ABL flow. However, recent experimental, forensic, and reconnaissance investigations revealed that the inadequacy of the current design practice. For example, the twenty-story Great Plains Life (GPL) building in Lubbock, Texas was structurally damaged with a significant amount of residual drift due to the F5 tornado in the business district of the city. In addition, the Mercy Hospital in Missouri, USA was rotated at its foundation by 101 mm during to the May 22, 2011, EF5 Joplin tornado. Sengupta et al. [80] reported that the peak loads exceed the ASCE 7-05 provisions for ABL wind load by 1.5 times for F2 scale tornadoes. Mishra et al. [59] from Texas Tech experimentally evaluated forces and pressure coefficients on a cubic building model placed in tornado-like wind field and demonstrated the inadequacy of scaling up non-dimensional pressure coefficients (C_p), obtained from straight-line wind, for evaluating tornadic loads. Sabareesh et al. [77] compared the surface pressure distribution on a cubic building under ABL and tornadic wind loading. Haan et al. [45] tested low-rise buildings placed in tornado-like flow field and reported peak loads up to 50% higher than ABL wind load provisions in ASCE-7-05. Thampi et al. [87] studied the interaction of tornadoes with a typical low-rise gable roof structure. A significant reduction in loads after complete roof failure was reported. Yang et al. [97] conducted PIV and force measurements on a high-rise building model and discussed the structure of highly turbulent wake zone around the building, along with variations in forces and moments with respect to building position. Case et al. [15] experimentally studied the effect of low rise building geometry on tornado-induced loads and highlighted the importance of adequate design of roof to wall connections for tornado-resistant (up to EF3) design of low rise building. Nasir and Bitsuamlak [66] computationally evaluated the effects of tornadic loads on a tall building. Nasir [65] investigated the effect of tornado-like wind on typical flat roof mid-rise building and high-rise building and discussed the resulting surface pressure distribution and forces with respect to building location and orientation. Vickery et al. [92] highlighted the problem in directly comparing external surface pressure coefficients due to tornadoes and ABL wind due to differences in normalizing velocity and due to local atmospheric pressure change experienced during tornadoes.

In recent years, the traditional prescriptive (single risk level) based design philosophy of buildings has been challenged by the concept of Performance Based Engineering (PBE) due to the new interests and expectations of the owners, designers, decision makers, and insurance industry [22,71,60,61,46], and [43]. In general, the decision-making community prefers economic terms over engineering demand parameters such as "drift," "acceleration," and "curvature." PBE has progressed with a reasonable success in earthquake engineering practice, where the PBE framework considers multiple performance levels, various hazard intensities, and advanced analysis methods to predict the performance of a facility due to future natural hazards, and tools to