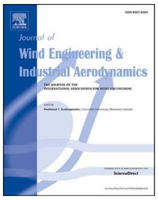
Journal of Wind Engineering & Industrial Aerodynamics 179 (2018) 260–272

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

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



Mathematical model and case study of wind-induced responses for a vertical forest

Qinhua Wang [a,*], Weidong Fu [a], Shuzhi Yu [a], Luke Allan [a], Ankit Garg [a], Ming Gu [b]

[a] Department of Civil and Environmental Engineering, Shantou University, Shantou City, Guangdong Province, China
[b] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, China

ARTICLE INFO

Keywords:
Vertical forest
Wind-induced responses
Vibration mitigation factor
Wind tunnel test

ABSTRACT

The concept of vertical forests is gaining popularity as it promotes the coexistence of architecture and nature in urban areas. The wind loads and dynamic responses of buildings may be impacted by the presence of vegetation. A wind-induced motion equation of vertical forests was formulated in the preliminary stage of research, assuming that tree cover is enclosed with curtain wall. The model was used to analyze a case. We used the time history of wind pressure attained from wind-tunnel tests of the host structure to calculate wind-induced responses. To investigate the contribution of the vegetation, three cases were analyzed: the original structure, the vertical forest and the host structure with an ETMD (equivalent tuned mass dampers). The impact exerted by tree cover with specific parameters on wind-induced responses was analyzed. The results show that tree cover significantly reduces vibration of the host structure under the action of wind loads, though the vibration-absorbing effects exerted by tree cover are less than that of the ETMD. Parametric analysis indicated that vibration-absorbing effects are more susceptible to the variation of natural frequency of tree cover than its damping ratio.

1. Introduction

Vertical forests comprise a new generation of high-rise urban buildings completely covered by various types of vegetation. This concept promotes the coexistence of architecture and nature in urban areas (Boeri, 2016). The vertical forest as shown in Fig. 1 (Boeri, 2016) has similar functions as that of green walls and green roofs in environmental aspects, the vegetation planted on buildings not only have aesthetic appeal (e.g., a changing landscape and extraordinary perspective) but also acts as a green filter that absorbs fine particles produced by urban traffic (Irga et al., 2017; Pettit et al., 2017). Vegetation also shields the balconies and interiors from noise pollution (Pathak et al., 2011), and reduces the urban heat-island effect (Bevilacqua et al., 2017; Perini and Rosasco, 2013). The buildings with green vegetation were found to achieve 26% reductions in energy use intensity and 32% reductions in CO_2 emission intensity in comparison to benchmark values (Balaban and Oliveira, 2016). Many projects based on the concept of vertical forests have been completed or will be executed, such as the vertical forest in Milan, Italy, the tower of cedars in Lausanne, Switzerland, the vertical forest in Nanjing, China and the tree tower in Toronto, Canada. Due to growing concerns about climate change, such projects can be expected to rise in fast-growing developing countries such as India, Brazil, and South Africa.

The vertical forest concept is currently on the rise due to the foregoing strengths. The first project involving a vertical forest, consisting of two residential towers of 110 m and 76 m in height, was completed in 2014 in the center of Milan, Italy (Boeri, 2016). Around 900 trees (each measuring 3, 6, or 9 m) and over 20,000 plants from a wide range of shrubs and floral plants were planted on the balconies on all sides of the two towers (Boeri, 2016). The second prototype vertical forest in Lausanne, Switzerland, consisted of a high-rise tower (36 floors with 117 m height) hosting 2400 plants and 100 cedar trees (Boeri, 2016). The third vertical forest project, comprising an office and a high-rise hotel, with heights of 200 m and 108 m, respectively, will be finished in 2018 in Nanjing city, China. The tops and balconies of these buildings will be home to 600 large trees, 500 medium-sized trees, and 2500 plants (World-Architects, 2017). The fourth vertical forest project are named as Toronto Tree Tower. It is an 18-story tree tower, which stands 62 m high and comprise 4500 sqm of residential area (Lynch, 2017).

Abbreviations: BRLC, background and resonant load component; DGLF, displacement gust loads factor; DOFs, degrees of freedom; ESWLs, equivalent static wind loads; ETMD, Equivalent Tuned Mass Damper; LRC, load-response correlation; MGLF, moment-based gust loads factor; OS, original (host) structure; RMS, root mean square; TMD, tuned mass damper; VF, vertical forest; WCMILC, weighted combination of modal inertial load component; NF, natural frequency.

* Corresponding author.

E-mail address: qinhuawang@stu.edu.cn (Q. Wang).

https://doi.org/10.1016/j.jweia.2018.06.007
Received 28 September 2017; Received in revised form 14 June 2018; Accepted 14 June 2018

Fig. 1. A vertical forest (Boeri, 2016).

Architects have considered methods of selecting plant species and planting patterns for tree cover. However, these issues have rarely been considered in wind-resistant design. There is a need for wind engineering researchers to consider the forgoing issues while studying the dynamic wind loads on the vertical forest and wind-induced responses of structures. Tree cover has the following effects: (1) The tree cover planted on balconies of buildings changes their exterior shape, which affects the overall drag of the building and hence the overall wind load. (2) Both a high-rise building and its tree cover, especially big trees, will vibrate under wind loads. Their vibrations are coupled (i.e., their dynamic responses influence each other); the tree cover may have the function of absorbing vibration, and could act as a set of small dampers. Wind-induced responses of vertical forests involve the interaction of wind-tree-structures, which is a very complicated research topic. In this study, only the interaction between the tree and structure is considered and tree cover was assumed to be enclosed behind a curtain wall. In other words, tree cover could be regarded as multiple tuned mass dampers (MTMD) installed in building structures. Research results concerning the effect of MTMD on wind-induced responses and dynamic characteristics of trees provided a valuable reference to this paper.

Regarding the effect of MTMD on wind-induced responses, Igusa and Xu (1994) first studied the application of MTMD for one-degree of freedom systems, they found that MTMD can be more effective than a single TMD with equal total mass. Kareem and Kline (1995) investigated the dynamic characteristics and effectiveness of MTMD under random loading conditions. It has been demonstrated that the MTMD configuration was a more effective means of controlling the motion of the primary system. Jangid (1995) investigated the effectiveness of MTMD in decreasing the dynamic response of base excited structures for first-mode vibration. Their results showed that MTMD were more effective and more robust than a single TMD with equal mass and damping ratio. Lewandowski and Grzymisławska (2009) analyzed the possibility of reducing the dynamic responses of frame structures with the help of MTMD under the strong wind loads. Their results indicated that the reduction of both displacements and accelerations of structures with MTMD was better than TMD. Patil and Jangid (2011) set up the governing equations of motion of the building with MTMD/TMD under wind loads and studied its optimum MTMD. They concluded that MTMD were quite effective and robust in the vibration-absorption of the benchmark building. Elias and Matsagar (2014) investigated MTMD distributed along the height of a high-rise building for their effectiveness in controlling vibration response. Their study showed that the peak displacement response reductions in the case of the single TMD, MTMD all at top floor, and distributed MTMD, respectively, were 15%, 40%, and 50%.

To calculate dynamic parameters and windthrow of trees, numerous mathematical models have been proposed. Kane and James (2011) studied dynamic properties, such as natural frequency and damping ratio of open-grown deciduous trees. Spatz and Theckes (2013) considered primary and higher-order branches as multiple tuned mass dampers and studied the oscillation damping in trees. Their findings showed that structural damping was critical for trees in order to withstand strong wind gusts. Ai et al. (2016) used a numerical model to simulate fluctuating wind velocity, and calculated the nonlinear dynamic responses of trees subjected to strong winds. Baker (1995) proposed a model to investigate the behavior of isolated trees in high winds by calculating base bending moment spectra, and described the development of the process of tree windthrow. Pivato et al. (2014) modeled the tree as a flexible cantilever beam. Vibration of the beam, induced by turbulent winds, was solved through modal analysis. Finite element models were applied to simulate the dynamic behavior and calculate tree oscillations (Moore and Maguire, 2008; Sellier et al., 2006). Wind-excited responses of aerial parts of an individual Norway maple tree were measured in a field study near the city of Freiburg, Germany and the results showed the importance of higher-order vibration modes decreases with increasing wind speed (Schindler et al., 2013).

As compared to tall buildings, research has rarely highlighted wind-induced responses of integrated vibration systems of tree cover and their host structures. In order to assess wind impacts on the tree cover planted on a high-rise building and the complex dynamics transmitted from trees to the structure, a 1:100 scale-model wind-tunnel test was performed at Milan Polytechnic (Boeri, 2016). Aerodynamic forces, moments were evaluated by wind-tunnel test of a base balance. Their results were used to assess the sizing and optimization of the distribution of trees on the facade of their host building. Wind-tunnel tests of full-scale trees and potted plants have been carried out at Florida International University in Miami. The plants were subjected to a test wind speed up to 67 m/s. In their test, the forces and moments at the base were measured to assess the forces transmitted to the building structures through turf and the root system (Boeri, 2016). Aly et al. (2013) investigated wind load on small- and full-scale trees used as part of green roofs and balconies. Small-scale wind-tunnel testing was conducted to understand the interference effects from surrounding structures, and full-scale trees were investigated at a large open-jet facility to determine the wind-tree interaction. Their research showed that the load coefficients of trees tend to be reduced at relatively high wind speeds.

Tree cover is assumed in this study to be enclosed within a curtain wall, which considers no interaction between wind and trees, and merely considers tree cover as a set of multi-dampers. A mathematical model of wind-induced responses is proposed for a vertical forest on that basis. A tree is modeled as a two-degree-of-freedom vibration system, and the structure hosting the tree cover is considered as a shear-type frame in this proposed model. Dynamic characteristics of vertical forest, i.e., natural frequencies, mode shapes, and transfer functions were discussed. Wind-induced displacement and acceleration responses, as well as equivalent static wind loads (ESWLs) of the vertical forest were calculated by applying the model to a 50-story structure. To probe into the vibration mitigation impact exerted by the vegetation cover, the wind-induced responses of the vertical forest, the host structure with ETMD, and the host structure were calculated. The effects of natural frequency and damping ratio of tree cover on transfer function of VF and wind-induced displacement responses were analyzed.