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Analysis of the probability of failure for open-grown trees during wind storms

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ABSTRACT

Although trees convey important environmental, economic, and sociological benefits on humans and society, they can also cause significant economic and societal disruptions, especially when subjected to wind storms in urban environments. Tools for proper assessment of the risk of these disruptions can be of significant benefit to society. In this research an approach to quantifying the failure probability for trees subject to wind storms is presented and illustrated by application to two specific maple trees in Massachusetts, USA. The approach entails four specific steps: (1) Random wind time history samples were generated using a modified Ochi–Shin spectrum, (2) these wind time histories were used as loading time histories on finite element models of the example trees in both summer (in-leaf) and winter (leafless), (3) maximum bending moments generated by the random wind time histories were compared to the failure (yield) moment of the tree at 1.4 m above ground, (4) the failure/fragility curves of the trees were estimated by Monte Carlo simulation for a range of average wind speeds and for 1000 independent wind time histories at each wind speed.

1. Introduction

Trees growing in residential settings (amenity trees) provide many environmental, economic, and sociological benefits [1], but tree failure can damage property and injure people—sometimes fatally [2]. Property damage and personal injury sometimes lead to costly litigation [3]. Arborists attempt to mitigate tree failure by proactively assessing risk [4], which is a combination of the probability of failure and the consequences of that failure. Wind is the primary cause of tree failure in many climates [5,6], and has been a subject of investigation in forestry for many years. Three different approaches have been developed: (1) qualitative assessments, (2) empirical or statistical models, (3) mechanistic models [7]. The first approach is based on observational tools [8,9]. The second approach provides better accuracy for a range of locations [3]. The third approach, using mechanistic models, is the most recent approach although it has been pointed out that mechanistic models, due to their deterministic nature and limitations in the idealization complicated systems such as trees, sometimes provide predictions which conflict with field observations [7]. Since the initial efforts to develop GALES [5] and HWIND [10], others (such as [11]) have continued model development. The FOREOLE model [12] considers both wind and snow loading in estimating the probability of failure. All of the models consider forest- or plantation-grown trees, which are morphologically different from amenity trees. The latter typically have broader crowns, more and larger branches, and a more tapered stem that often splits into multiple, co-dominant stems.

In addition to considering amenity trees rather than forest or plantation trees, another novel aspect of the current study is the consideration of the failure of individual trees, whereas most previous models operate on the scale of the forest stand or plantation. The current study also employs finite element (FE) modeling while considering randomness in wind speeds, evaluating tree response based on a dynamic time history analysis. Existing mechanistic models attempt to capture the complex tree dynamics with an empirically-determined gust factor [7], that may have limited application outside of the region where it was determined. The use of Monte Carlo (MC) simulations, while computationally expensive [13], is a conventional method in probabilistic structural analysis. For systems with appreciable probabilities of failure, such as trees, MC simulations can provide accurate results with a relative degree of efficiency. The analysis of probability of failure that is at the heart of this method computes the cumulative probability of system failure at specified mean

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wind speeds [14]. In the current case, failure is defined as occurring when the bending moment at 1.4 m induced by the wind exceeds the bending moment capacity of the stem at 1.4 m. The moment capacity is defined as the moment that generates extreme fiber compressive stress equal to the compressive yield stress of the wood.

The objective of this study is to propose a method for estimating the probability of failure at specified mean wind speeds leading to failure/fragility curves for amenity trees due to wind storms. The method described here is broadly applicable to probabilistic analysis of trees using many possible sets of modeling assumptions. To show how the method may be applied in practice and to provide guidance in presenting and interpreting results, failure/fragility curves are presented for two example sugar maple trees (*Acer saccharum* Marsh.). Additionally, this study includes the effect of decay and leaves on the probability of failure. The examples are instructive regarding application of the method and interpretation of results, but within the scope of this paper several key modeling assumptions regarding tree geometry, aerodynamic characteristics and dynamics have been made. In applying the proposed method to trees for the purpose of a complete risk analysis these assumptions should be carefully considered and in some cases more detailed or complicated models may be appropriate.

2. Methods

2.1. Modeling approach and parameters

Dynamic time history analysis of a 3D finite element model of the trees is at the core of the proposed approach. This approach has previously been used by the authors in a deterministic study of tree dynamics [15]. The finite element models use beam elements of varying cross sectional dimensions to model stem and branch taper, assume a fixed support condition at the base, 5% damping for the winter state of the tree and 15% damping for the summer state of the tree (the large difference in damping is due to the additional aerodynamic damping provided by the leaves). The summer damping of Tree-1 was measured at 15% [16]. Winter damping of 5% was assumed based on [17,18] who found that summer damping was three times winter damping for Bradford pears (*Pyrus calleryana* Decne. 'Bradford') and red oaks (*Quercus rubra* L.). Because the crown width of Tree-9 was similar to Tree-1 and Kane et al. [16] found that crown width of sugar maples was proportional to damping, Tree-9 was assumed to have the same summer and winter damping ratios. This assumption was made in the absence of an experimental measurement and consistent with the literature cited above. Experimental measurement of the four damping cases (Trees 1 and 9 in summer and winter) would certainly improve the accuracy of the finite element models. However, to illustrate the application of the method described here, simplifying assumptions regarding damping have been made that, in light of the existing literature and some recent measurements, are reasonable. The two sugar maple trees are located (1) in Belchertown, MA (42.28018°N, 72.407735°W) and (2) at the University of Massachusetts, Amherst, MA (42.273278°N, 72.414547°W) and were modeled using ADINA 8.5 (ADINA Software, Watertown, MA, USA). Photographs and FE models of both trees are shown in Fig. 1. The size and crown architecture of each tree were measured as described in [15]. Tree-1 has 10 branches and a stem diameter of 0.53 m, while Tree-9 has 29 branches and a stem diameter of 0.66 m. Material properties were assumed from [19,20] as described in [15]. Drag (F_D) on each segment in the FE model was calculated as

$$F_D = \tfrac{1}{2}\rho U^2 A C_D \tag{1}$$

where ρ is the air density [kg/m^3], A is frontal area [m^2], U is wind speed [m/s], and C_D is the non-dimensional drag coefficient. It is important to note that Eq. (1) neglects the interaction between the dynamically deforming tree and the wind field—a variety of fluid structure interaction. Such interactions can be meaningful [21,22] but modeling such interactions in dynamic time history analysis within a Monte Carlo framework is computationally prohibitive within the scope of this study since modeling such interactions requires a computational fluid dynamics model capable of modeling turbulence at length scales smaller than branch diameter as well as a structural mechanics model. Coupling the models imposes additional, significant, computational burdens. The first order calculation of wind loading presented in Eq. (1) has therefore been adopted here. Since wind speed varies with height (z) above ground [23,24], U was assumed to vary with height (z) according to the relationship proposed by [25]

$$U(z) = U_h\left(\frac{z}{h}\right)^{1/7} \tag{2}$$

where U_h is the reference wind speed at height h.

The response of each tree was modeled in winter and summer. In temperate climates, several relevant parameters change between the seasons. In addition to different values of ρ (1.226 kg/m^3 for summer and 1.326 kg/m^3 for winter), C_D was assumed to be 1 in winter (because stem and branch segments were modeled as cylinders). In summer, C_D was assumed to vary with U in accordance with an empirical relationship [26]. Frontal area in winter was defined as the exposure area of the stem and the branches (modeled as cylinders); in the summer, it was estimated from an empirical relationship for smaller red maples (*Acer rubrum* L.) (Kane, unpublished data, see Fig. 2). For Tree-1 and Tree-9, frontal area in summer was 3.9 and 2.5 times, respectively, larger than frontal area in winter. Estimation of frontal area from tree morphometry was necessary in this case because photographs of the trees did not allow direct measurement of the frontal area due to the presence of significant background vegetation. Published studies on the relationship of leaf area to stem diameter [27–29] show that such predictions are generally possible, but none of those studies address frontal area rather than leaf surface area and none include trees from the northeast United States. The data of Fig. 2 have therefore been used to predict frontal area. The data were collected using an established method [26] that has been used to assess frontal area of multiple tree species [30]. The data reflect smaller trees of a different species than the trees studied here, but Nowak [27] has shown that relationships between morphometry and leaf area are largely consistent across species and genera. Although there are many intricacies in predicting the frontal area of these trees, consistently using an established method to predict frontal area makes it reasonable to apply the probabilistic approach described here since the primary objective is to introduce the method and compare two trees for which it was not possible to measure frontal area accurately.

2.2. Stochastic wind model

The Ochi–Shin equation

$$S_{Vw}(\omega) = \frac{C V_w^2 F_g}{\omega} \tag{3}$$

which had been developed to define the wind spectrum for offshore areas [31], was modified to correspond to the local terrain of the example trees by altering the surface drag coefficient (C).