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# Uncertainty analysis of the strength capacity and failure path for a transmission tower under a wind load

Xing Fu [a,*], Hong-Nan Li [a,b]

[a] Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116023, China
[b] School of Civil Engineering, Shenyang Jianzhu University, Shenyang 110168, China

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ABSTRACT

Many tower structures have collapsed during strong wind events; therefore, the objective of the present study is to estimate the strength capacity of transmission towers accurately and to identify all potential failure modes. An uncertainty analysis method for tower structures subjected to a wind load is presented. Subsequently, random samples of material properties and section dimensions are generated based on the Latin Hypercube Sampling technique and then used to establish uncertain finite element models for transmission towers. A static non-linear buckling analysis for structures subjected to a wind load is conducted using ANSYS software. Based on tower models incorporating uncertainty, our analysis reveals that there are six possible initial failure tower members but only one for the deterministic model, indicating that the uncertainties regarding material properties and section dimensions should be taken into account. Furthermore, a sensitivity analysis is conducted, and the results reveal that the uncertainty of material properties has a stronger influence than the uncertainty of section dimensions. Finally, the influence of wind attack angle is discussed, and the initial failure positions and corresponding probabilities for various wind attack angles are obtained. The results show that the most unfavorable wind attack angle is 0° and that the most probable failure position of the tower of interest is the middle of the tower body.

## 1. Introduction

Transmission lines carry electricity and act as the intermediate link for transporting and distributing electric power. The basis of grid interconnection is transmission lines spanning geographical regions. The modern large power grid offers many advantages; however, the probability of local failures leading to large-area power outages is increasing. During a typhoon or hurricane, the failure of transmission lines can lead to paralysis of the power grid, directly affecting subsequent construction, living quality and disaster assistance and potentially causing severe secondary disasters. Historically, numerous transmission lines have collapsed during severe gales and thunderstorms (Fu et al., 2015a). Thus, it is imperative to study the strength capacity of transmission towers under strong winds and characterize the failure modes to ensure safe operation of the power grid.

High intensity winds (HIWs), associated with tornadoes or microbursts, have attracted much attention due to their strength and association with multiple tower failure accidents (Aboshosha et al., 2016). Savory et al. (2001) performed a dynamic analysis of a lattice tower for two HIW events; the results indicated that tornado-induced failures correlate well with the cumulative evidence in this disaster context, whereas the influence of microbursts is less severe in the configuration modeled in that study. Shehata et al. (2005) presented a procedure to model and predict the behavior of a transmission line structure subjected to downburst wind loads. For tornado events, the main issue is to determine the most unfavorable locations, which can be defined by the angle of attack and the relative distance between the tornado and structure. Hamada and El Damatty (2011) performed large parametric analyses by varying those two geometric parameters to identify critical tornado locations. Accordingly, Hamada and El Damatty (2015) studied the strength capacity of two guyed transmission lines and concluded that the two selected towers could not withstand the maximum velocity of an F2 tornado.

The above analyses were conducted in a quasi-static manner that can assess the critical wind speed and tower failure members accurately. For simulating the progressive collapse deformation, however, the static method is insufficient. The progressive collapse should be performed in an explicit environment, and either the ANSYS or ABAQUS commercial software program is typically used to simulate structural collapse. Multiple collapse simulations of high-rise buildings have been conducted, whereas the progressive collapse analysis for transmission towers is relatively

* Corresponding author.
*E-mail address:* fuxing@dlut.edu.cn (X. Fu).

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limited. Wang et al. (2013) proposed a progressive collapse analytical procedure for a transmission tower-line system under an earthquake in which members will fail once exceeding their yield strength. On this basis, Zhang et al. (2013) simulated the collapse deformation of a tower-line system induced by a wind load. For the transmission tower, the immediate cause of collapse is not the material strength but rather buckling of a member due to the presence of initial eccentricity (Fu et al., 2016). Tian et al. (2016) incorporated member buckling into the user subroutine VUMAT in ABAQUS and then simulated the progressive collapse of a tower-line system. The benefit of explicit analysis is the fast calculation speed (at the expense of accuracy). The application of progressive collapse for a tower-line system is intended to help researchers understand the weak positions and failure process more clearly.

The aforementioned analyses are based on the deterministic tower model, which means that the material properties and geometric dimensions are deterministic and adopt standard values. However, the material strength and geometric dimensions are variable in practice. Typically, structural models that incorporate uncertainty are generated based on stochastic selection of the values of material properties, such as the weight density of the reinforced concrete (RC), the yield strength and the elastic modulus of the steel material, the peak strength and the strain at the peak strength of the cover concrete, and the peak strength, the strain at the peak strength, the residual strength and the strain at the residual strength of the core concrete (Yu et al., 2016). Dolsek (2009) extended the incremental dynamic analysis (IDA) by introducing a set of uncertain structural models in addition to the set of ground motion records. Lu et al. (2014) derived the analytical formulations of two types of seismic fragility functions, using a five-story RC frame designed according to the Chinese codes as a case study. The results demonstrated that the capacity randomness and the selection of earthquake intensity measures had a strong influence on the predictions of seismic fragility and risk. Yu et al. (2016) assessed the effects of structural randomness on limit state capacities and recommended dispersion values for the states of slight damage and collapse. Parisi and Sabella (2017) conducted a fragility analysis of an RC building exposed to a flow-type landslide, considering the uncertainties in the landslide impact loading, material properties, size and reinforcement of members, and capacity models. Fu et al. (2016) developed fragility curves for transmission towers under a wind load within the uncertainty of wind only. Park et al. (2016) calculated the seismic fragility curves of high-voltage transmission towers using a deterministic structural model. Uncertainty analysis techniques for RC structures have long been studied and have produced significant results. However, few fragility analyses exist for transmission tower structures, and none of these studies involve the uncertainty of material properties and geometric dimensions.

Based on a review of collapse predictions for the transmission towers and the uncertainty analysis, it can be concluded that the dynamic or collapse responses for transmission towers under strong wind are unique due to the deterministic nature of tower models. In other words, the deterministic analysis can only obtain one failure mode, and many other potential failure modes are omitted. To fill such a gap, it is crucial to introduce an uncertainty analysis method into the analysis of transmission tower stability to identify all possible failure paths and estimate the strength capacity accurately. In Section 2, the uncertainty analysis process for tower structures subjected to a wind load is provided. Then, the random samples of material properties and section dimensions are generated in Section 3, followed by the proposal of an uncertain finite element model for a transmission tower in Section 4. Such a model is applied to perform the uncertainty analysis. Section 5 lists the calculated results within the sensitivity analysis and the influence of the wind attack angle, and Section 6 concludes the study.

## 2. The proposed uncertainty analysis process for transmission towers subjected to wind loading

The deterministic finite element model (FEM) cannot be used to

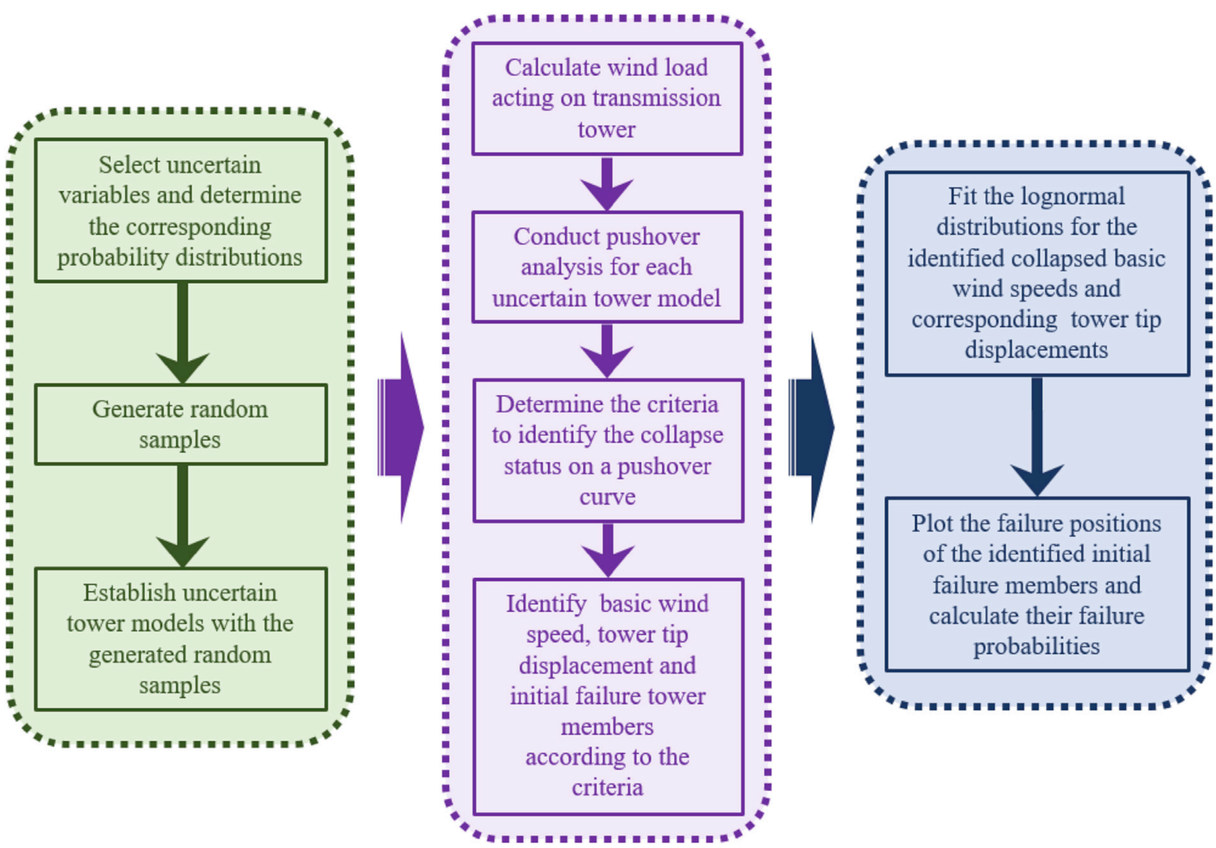


**Fig. 1.** Flow chart of uncertainty analysis for a transmission tower subjected to a wind load.