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# An equivalent boundary model for effects of adjacent spans on wind reliability of wood utility poles in overhead distribution lines

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ABSTRACT

Overhead distribution lines in the United States are primarily supported by wood poles. These utility poles are vulnerable to high wind loads from hurricanes which has resulted in a large number of power outages during past hurricanes, especially in coastal areas. Risk management of distribution systems requires development of distribution line models to reliably assess their performance under hurricanes. However, modeling the entire distribution line is not practically feasible as they are very long and consist of a large number of spans. The present study proposes analytical models to capture boundary effects of adjacent spans on the wind response of the pole of interest via equivalent springs and wind-induced forces. The stiffness of conductors (cables) is derived through a simplified solution that considers the shape of the conductors under lateral static gust wind and gravity loadings; this model is shown to be very accurate when compared to the exact analytical as well as Finite Element solutions. Deterministic and probabilistic studies are performed to assess the impact of boundary conditions on the performance of the poles; results indicate that pole boundaries may have a considerable impact on the estimates of failure probabilities especially when the extent of difference in the properties of adjacent spans is not negligible. Specifically, neglecting boundary effects from neighboring spans may result in underestimation of failure probabilities of stronger poles and overestimation of failure probabilities of weaker poles as load sharing effects among the poles are not considered. The proposed boundary model enables more reliable hurricane risk assessment of power distribution systems to effectively manage the risk of outages.

## 1. Introduction

Electricity supports various activities in a society and any disruption in its constant flow may result in large economic loss. The infrastructure supporting electricity faces risk of damage from various natural hazards such as hurricanes, especially in coastal areas. Hurricanes are responsible for the majority of power outages in the United States. For instance, in 1992, hurricane Andrew caused 1.4 million customers to lose their power in Florida [1]. Also, Hurricane Sandy in 2012 caused 8.5 million customers to lose power leading to over $50 billion in economic loss [2]. The electrical power system consists of three major units including generation, transmission and distribution; among these, distribution lines suffered extensive damage during past hurricanes [3]. In the United States, the majority of utility poles are made of wood. Although poles made of wood are widely available and less costly, they sustain considerable damage especially under strong wind hazards. Past hurricanes caused severe damage to distribution lines. In 1989, Hurricane Hugo destroyed over 15,000 poles, over 6000 transformers and about 700 miles of conductors (cables) [4]. In 2005, over 12,000 Florida Power and Light (FPL) utility poles were failed during Hurricane Wilma and Hurricane Katrina [5].

The high vulnerability of distribution lines during past hurricanes highlights the need for risk assessment methods in order to manage the risk of outages induced by failure of distribution systems. Such risk assessment methods require reliable performance assessment of distribution lines using models that can capture their actual behavior during extreme wind events. A distribution line can be as long as several miles with hundreds of poles. Therefore, numerical modeling of the entire system using methods such as Finite Element techniques to analyze the performance of distribution lines under wind loadings is not practical. A solution to this problem is to assume that all poles and all spans in the distribution line are the same; therefore, effects of neighboring spans can be neglected. Shafieezadeh et al. [6] developed

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fragility models of aged Southern Pine wood poles for the US region. In their analysis, potential effects of neighboring spans were not considered and only the pole of interest was modeled. This simplifying assumption was used in a number of studies on the wind performance of poles and distribution lines in the US and other areas [7–9]. However, this simplifying assumption may not produce accurate results for actual distribution lines. In order to have a reliable electric distribution system, utility poles are inspected every few years [10]. Based on the inspection results, some of the decayed and damaged poles are strengthened or replaced by new poles. Therefore, in an actual distribution line, it is very likely that the age distribution of the poles and, in general, their condition state is not uniform. Depending on the extent of difference between properties of adjacent poles and spans, boundary conditions may have a significant impact on the performance of the poles and spans of interest. It should be noted that if there is any considerable change in the stiffness and wind-induced forces in the neighboring spans, boundary effects must be considered. Factors that can result in the variation in the stiffness of poles is not limited to the age of the poles; geometry of the poles, span length, number and diameter of conductors, and wind speed and its direction are among significant variables that can also cause variation in the stiffness and the wind-induced forces in adjacent spans.

The present study proposes a model based on equivalent static boundary conditions to capture impacts of neighboring spans for wind performance assessment of distribution lines. The boundary model consists of equivalent springs and forces corresponding to the stiffness of the poles and lines and wind-induced forces over the length of the distribution line. To obtain the equivalent boundary conditions, the exact model for three-dimensional deformed shape of conductors is derived considering general boundary conditions when conductors are subjected to static gust wind and gravity loadings. Furthermore, a simple parabolic approximate model is derived for the deformed shape of conductors. These two models are validated against Finite Element solutions for conductors. Using the approximate model, a stiffness matrix and a force vector are assembled to account for the wind response of distribution line segments considering the variation of stiffness in the spans and corresponding wind-induced forces over the length of distribution lines. Based on these models, a static boundary condition for the effects of adjacent spans is defined through an equivalent stiffness and equivalent force. Using these models, a series of deterministic and probabilistic studies are conducted on a set of wood utility poles of different ages in a long overhead distribution line. The rest of this paper is outlined as follows: Section 2 presents the derivation of the analytical boundary condition model for utility poles. Section 3 explains the process for determination of failure probabilities given the age of the poles and boundary effects. Results of numerical studies and conclusions of this research are presented in Sections 4 and 5, respectively.

## 2. An analytical boundary condition model for utility poles

### 2.1. Model description

Since distribution lines are very long and consist of a large number of spans, modeling the entire system is not practically feasible for performance assessment of utility poles. As shown in Fig. 1a, poles in a distribution line are connected through conductors. (In the United States, cables that are used in electric power lines to carry electricity are often called "conductors".) Therefore, the response or performance of any segment of a distribution line is impacted by the rest of the system. This study proposes equivalent boundary conditions to capture the impact of the neighboring spans to assess the wind response of a single utility pole, represented by $P_i$ in Fig. 1a. However, the methodology can be utilized to define the boundary conditions for any segment of a distribution line. As shown in Fig. 1b, under static analysis, the impact of the rest of a distribution line on the pole of interest can be defined through the equivalent boundary conditions which are composed of an equivalent spring representing the stiffness of the adjacent spans and a wind-induced equivalent force to account for the forces applied from neighboring spans to the pole of interest. In Fig. 1a, pole $P_i$ is considered as the pole of interest. In this study, it is assumed that the direction of wind (transverse-y direction) is perpendicular to the distribution line (longitudinal-x direction). This assumption represents most probably the worst case scenario for the impact of wind on overhead distribution lines; this is due to

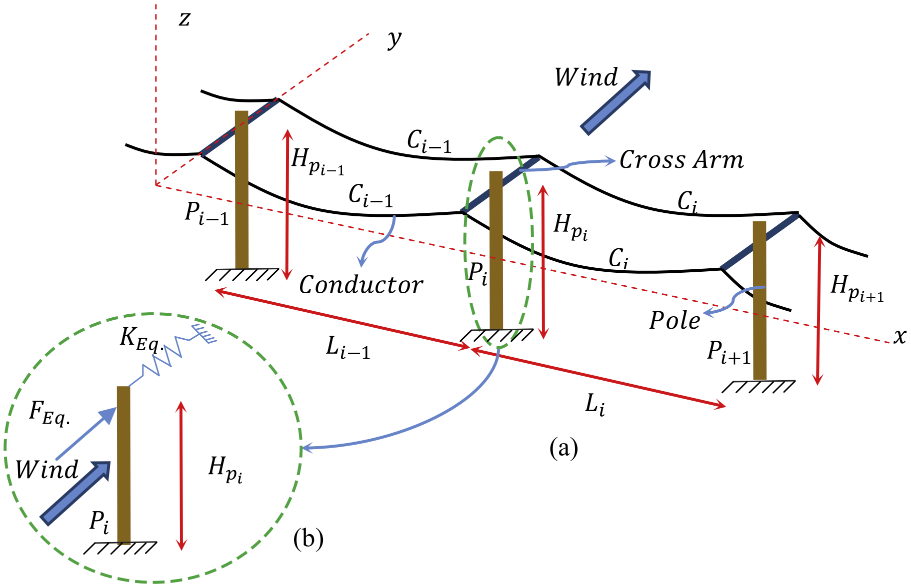

**Fig. 1.** Schematic of a typical distribution line: (a) configuration and constitutive components of the distribution line and (b) the pole of interest with equivalent boundary conditions.