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Finite element modelling of pre-stressed concrete poles under downbursts and tornadoes

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ABSTRACT

Among different types of electrical transmission line structures, pre-stressed concrete transmission poles have the advantages of low installation and maintenance cost, appropriate delivery time, and high corrosion resistivity. Typically, these concrete poles are designed to resist only synoptic wind loading as current codes do not consider high intensity wind events in the form of downbursts and tornadoes. To the best of the authors' knowledge, this study is the first investigation to assess the behaviour of pre-stressed concrete poles under High intensity wind events. Due to the localized nature of those events, identifying the critical locations and parameters leading to peak forces on the poles is a challenging task. To overcome this challenge, a built in-house numerical model is developed incorporating the following: (1) a three-dimensional downburst and tornado wind field previously developed and validated using computational fluid dynamics simulations; (2) A computationally efficient analytical technique previously developed and validated to predict the non-linear behaviour of the conductors under non-uniform loads resulting from those events (3) a non-linear finite element model developed in the current study to simulate the structural behaviour of pre-stressed concrete poles considering material nonlinearity. The non-linear finite element model, is validated using experimental data available in the literature. Extensive parametric studies are conducted using the numerical model to determine the critical downburst and tornado configurations leading to peak overturning moment acting on a pole which is designed to remain un-cracked under synoptic wind load. Failure studies are then conducted to assess the downburst and tornado velocities that would lead to a full collapse of the pole.

1. Introduction

Downbursts and Tornadoes are a category of weather storms that are referred to as high intensity wind (HIW) events. Those events are characterized by high wind speeds that affect a relatively narrow area. They are different than large scale events, such as hurricanes, because of their localized size and effect. Transmission lines are among the structures that are very sensitive to HIW. This is because of their length that typically extends for many kilometers making the probability of localized wind events, such as downbursts and tornadoes, to affect one of the towers of the line very high. As a result, many failure incidents of transmission line structures have been reported around the world. Dempsey and White [1] stated that 80% of weather- related transmission line failures around the world were caused by HIW events. Howes and Dempsey [2] stated that more than 90% of 94 structural failure events in Australia were induced by severe thunderstorms, including downbursts. Zhang [3], reported the failure of 18 transmission towers carrying 500 kV lines and 60 towers carrying 110 kV lines in 2005 because of various wind events including downbursts, tornadoes and typhoons. In Canada, many of transmission line failures occurred in the past twenty years as a result of downbursts and tornadoes such as those reported by Manitoba Hydro [4,5].

The above failures led to the initiation of an extensive research program at the University of Western Ontario, Canada, to study various aspects related to this problem. The research included development and validation of the HIW wind fields based on numerical simulations. Shehata et al. [6] developed a comprehensive structural analysis numerical model that incorporated the downburst wind fields and simulated various components of a transmission line system including the towers, insulators and conductors. Hamada et al. [7] developed a similar model that incorporated the tornado wind fields. Because of the localized nature of HIW events, the simulations conducted by these numerical models involved a large number of analyses involving varying the size and the location of the downbursts and tornadoes. The purpose was to determine the configurations leading to peak internal forces in transmission line members. As a result, the computational time needed to quantify the peak internal forces in all members of a tower is

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significantly large mainly because of the nonlinear analyses required to predict the conductors' responses. In order to solve this issue, Aboshosha and El Damatty [8] developed a semi-analytical solution to predict the response of conductors to the non-uniform loading associated with tornadoes and downbursts. All of the above studies focused on steel transmission line systems consisting of lattice steel towers. Another type of structures commonly used in transmission line systems is the pre-stressed concrete poles. Typically, this types of poles are self-supported, guyed or H-framed. Figs. 1a and 1b shows photos of different types of poles.

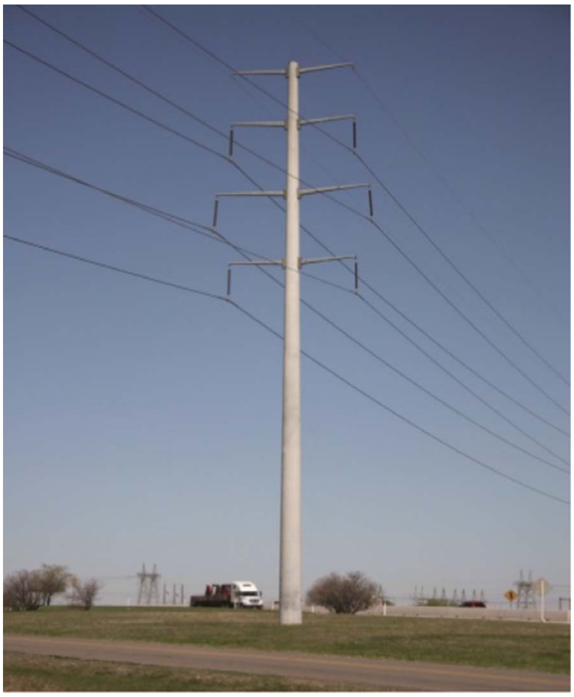

Fig. 1a. Cantilever Concrete Pole http://www.valmont.com/valmont/markets/utilities/transmission-poles.

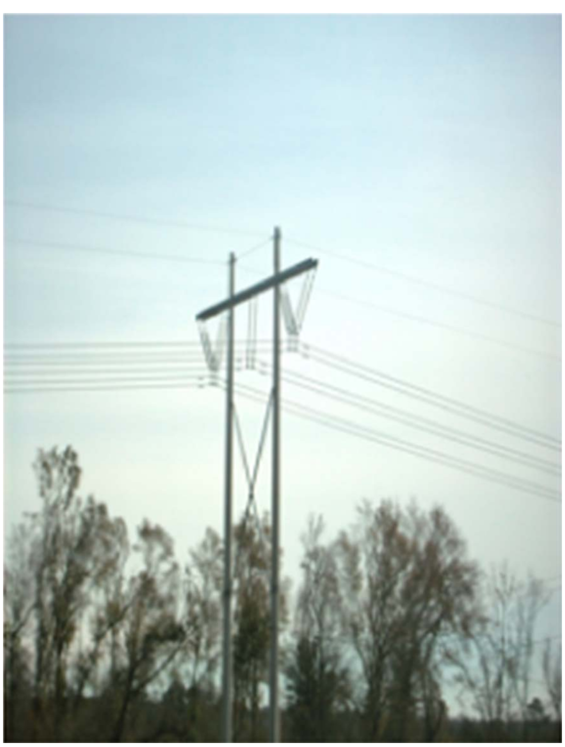

Fig. 1b. H-Frame Concrete Pole https://www.flickr.com/photos/81578389@N00/4283617188.

The advantages of the pre-stressed concrete poles are the low installation and maintenance costs, short construction time and corrosion resistivity. Reviewing the literature, it is found that no previous studies have been conducted to investigate the behavior of pre-stressed concrete poles to HIW events. In 2007, in Kitchener, Canada, a number of pre-stressed concrete poles failed during a high wind storm [9]. The failure was attributed to the excessive forces acting on the conductors.

The main objective of the current study is to develop a numerical model capable of predicting the behavior of pre-stressed concrete poles to HIW events, taking into account the variation in the location of those events. In terms of numerical simulation, the main difference between pre-stressed concrete poles and steel towers is the modelling of the material behavior. Since tornadoes and downbursts are extreme events, it would be reasonable to accept cracking to happen in a pre-stressed concrete pole once subjected to those events as long as no collapse occurs. As such, the material model should be able to predict the post cracking behavior of the poles under HIW loading.

The numerical model developed in this study incorporates:

(1) The three-dimensional downburst and tornado wind fields previously developed and validated in [10,11], respectively.
(2) The computationally efficient semi-analytical technique developed and validated in [8] to predict the non-linear behavior of the conductors under HIW while accounting for the effects of the conductors' pretension forces, sagging and insulator's stiffness.
(3) A non-linear finite element model developed in the current study to simulate the structural behavior of the pre-stressed concrete poles considering the material non-linearity and the pre-tensioning losses.

The paper starts by providing a brief description of the downburst and tornado wind fields used in the study. The first two components of the model (wind field and conductors modelling) were previously validated. As such, a validation is conducted in the current study for the developed non-linear finite element model by comparing its prediction to the results of tests conducted on pre-stressed concrete poles and reported in the literature. The developed and validated numerical model is then used to simulate a pre-stressed pole as a case study. The pole is designed under the loads specified by the ASCE-74[12] guidelines. Those guidelines do not consider HIW loads. The design follows the specifications described in the ASCE-123[13] guidelines which focus on pre-stressed concrete transmission line poles. The poles are designed to sustain normal wind loads up to a certain speed such that it remains uncracked.

Parametric studies are then conducted to determine the most critical downburst and tornado configurations for this pole. Non-linear analyses are also conducted to determine the downburst and tornado velocities that this pole is able to sustain before full collapse. A comparison between the effect of the downburst and tornado critical load cases is made.

2. Downburst wind field

Fujita [14] defined a downburst as a mass of cold and moist air that drops suddenly from a thunderstorm cloud base and impinges the ground surface and then transfers horizontally. As mentioned earlier, the localized nature of the downbursts makes field measurements hard to obtain. Limited full-scale measurements were reported in literature [15–19]. As such, numerical simulation of such events is considered a useful mean to estimate wind field velocities. A Computational Fluid Dynamics (CFD) model was developed in [10]. This model simulated the spatial and time variations of the wind field associated with downbursts. The downburst outflow in this model consists of two velocity components: radial (horizontal) component (V_{RD}) and axial (vertical) component (V_{VL}). The values of the two velocity components at a specific point in space are functions of its height relative to the