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# Failure analysis of guyed transmission lines during F2 tornado event

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ABSTRACT

Motivated by many failure incidents observed worldwide of transmission line structures during tornadoes and by the lack of appropriate design procedures accounting for loads associated with such events, an extensive research program focusing on this subject initiated at The University of Western Ontario, Canada, few years ago. The current study is a part of this research program, where a numerical model that can predict the capacity and the failure mode of a transmission line system under tornadoes is developed and validated. In this numerical model, the tornado wind field is obtained from previously conducted and validated computation fluid dynamics simulations. Two different lattice transmission towers are considered for failure analysis under the developed numerical model. Due to the localized nature of tornadoes, the forces acting on a structure depends on the location of the tornado relative to the structure. As such, a parametric study is first conducted by moving the tornado in space in order to identify the critical tornado locations leading to peak forces in the tower members. Failure analysis of each system is conducted under the two most critical tornado locations identified from the parametric studies. The analysis is conducted incrementally by gradually increasing the tornado velocity till reaching the peak F2 tornado velocity. The critical velocity at which a full collapse of a tower is determined. The effects of inclusion of geometric nonlinearities and of the assumptions made regarding post yielding behavior of tension members on the failure capacity are also assessed in the study. While both transmission tower systems are shown to fail at critical velocities less than the maximum F2 tornado velocity, significant difference in those critical velocities is observed between the two considered systems.

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## 1. Introduction

Electricity plays a vital and essential role in our daily lives. Almost all businesses and activities depend on having a reliable continuous source of electricity. Transmission lines are responsible for delivering electricity by carrying it from the source of production to the distribution systems. Failure of transmission lines can have devastating social and economical consequences, so it is imperative to understand how failure occurs, and how to prevent it. As stated by [1], more than 80% of weather-related transmission line failures world-wide are found to be attributed to high intensity wind (HIW) events in the form of downbursts, and tornadoes.

In Canada, tornadoes occur in almost all the southern regions of the country, such as in southern Alberta, Manitoba, Saskatchewan, Ontario, and Quebec. Ishac and White [2] reported that of all the populated areas in Canada, southwestern Ontario experiences the highest rate of tornado incidences; about two tornadoes per 10,000 km$^2$ every year, and most of the transmission line failures in this area are caused by tornadoes. 92% of these tornadoes were F2 or less on the Fujita scale. Newark [3] concluded that, on average, a F3 tornado occurs in southwestern Ontario every five years. Despite these facts, the codes of practice, design guidelines, and utility companies' design methodologies are based on the loads resulting from large-scale synoptic events with conventional boundary layer wind profiles. Conventional wind profiles are characterized by a monotonic increase in velocity with height, which is different than wind profiles attributed to tornadoes where the maximum wind speed occurs near the ground [4]. In addition, tornadoes are localized events with relatively narrow path widths. Also, a significant vertical wind component (uplift) exists in the tornado wind profile, which does not exist for synoptic winds.

Although it has been well reported that high intensity wind (HIW) events are responsible for most weather-related transmission line failures, very few studies were done to assess these failures. Shehata and El Damatty [5] assessed the failure of one of the transmission towers that collapsed in 1996 during a microburst event in Winnipeg, Canada. Their developed in-house numerical model was able to predict failure modes and progression of

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failure compatible with the post event field observations. The study predicted three possible failure scenarios and the progression of failure of each case was described in details. Savory et al. [6] conducted a research study on a self-supported transmission tower under both microburst and tornado wind loadings. The study investigated the tower behavior and failure modes under specific microburst and tornado parameters. The loading on the conductors and ground-wires was not considered in this study. In addition, only the effects of radial velocity component of the microburst and tangential velocity component of the tornado were considered on the transmission tower. The predicted failure mode showed that the horizontal shear force was the main reason for the collapse of the tower. In addition, no significant dynamic effect was found due to the translational movement of the tornado. Ladubec et al. [7] studied the effect of secondary moment (*P*-delta) on the response of transmission towers under a downburst wind field. The analysis used nonlinear space frame elements to simulate the tower members. The study showed an increase of 20% compared to the linear analysis in the peak axial forces in the tower main legs' chord members. The study is considered an improvement to the linear analysis of transmission towers that was performed by [5].

An extensive research program was initiated few years ago at the University of Western Ontario, Canada on the effect of tornadoes on transmission line structures. In the first study conducted by Hamada et al. [8], a numerical model for predicting the behavior of transmission lines under tornadoes was developed. The numerical model incorporated flow fields for F4 and F2 tornadoes based on computational fluid dynamics simulations conducted and validated by Hangan and Kim [9]. The towers and the conductors were simulated using three dimensional finite element models using the commercial software SAP 2000 (CSI Inc. 2010). Hamada and El Damatty [10] used this model to study in detail the behavior of a transmission line system under both F2 and F4 tornadoes. The study started by assessing the dynamic effect resulting from the translation motion of tornadoes. The main conclusion of this part of the study is that such an effect can be neglected and a quasi-static analysis is adequate. One of the challenges in assessing the behavior of transmission lines under tornado loads is that the peak forces vary with the location of the center of the tornado relative to the center of the tower of interest, which is defined by the angle of attack as well as the relative distance between the tornado and the structure. Accordingly, Hamada and El Damatty [10] conducted large parametric studies by varying those two geometric parameters in order to determine the critical tornado locations leading to peak internal forces in various members of the tower. The sensitivity of the tower members' internal forces to the variation of the location of the tornadoes was also assessed in the same study.

Later, El Damatty and Hamada [11] conducted a preliminary investigation to assess the vulnerability of two transmission line systems to failure under tornado loading. The numerical model, based on the commercial code [8], was extended to include a nonlinear model for the tower members. The study was confined by the limitations of the commercial code including the material model for the members, which were assumed to maintain their capacity after reaching their ultimate strength values. No tension failure was defined for the supporting guys. The study focused only on determining the critical velocity at which overall collapse is predicted to occur in view of the limitations of the assumed material model. No attempt was made in this study to describe the failure modes. Those limitations are overcame in the current study by developing a nonlinear in-house numerical model capable of predicting the failure load, progressive collapse, and failure modes of transmission lines under tornadoes.

Two guyed transmission line systems are considered in this paper as case studies. Using the developed numerical model, failure studies are conducted for each system. The failure studies included two critical tornado configurations, selected in view of the parametric studies conducted by Hamada et al. and Hamada and El Damatty [8,10]. In addition, each failure study case was repeated twice using different two material models describing the post yield behavior of tensions members. The objectives of this study are to gain an insight about the resilience of lattice transmission towers against failures when experiencing an F2 tornado, to describe the failure modes under such events, to assess the effect of different assumptions regarding post yield tension behavior, and to quantify the effect of inclusion of geometric nonlinearities in this type of analysis.

## 2. F2 tornado wind fields

A computational fluid dynamics (CFD) model for a small-scale tornado model was developed by [9]. Firstly, the CFD analysis was conducted using a swirl ratio $S$ of 0.28, where $S$ is the ratio between the tangential and radial velocities at the inlet boundary.

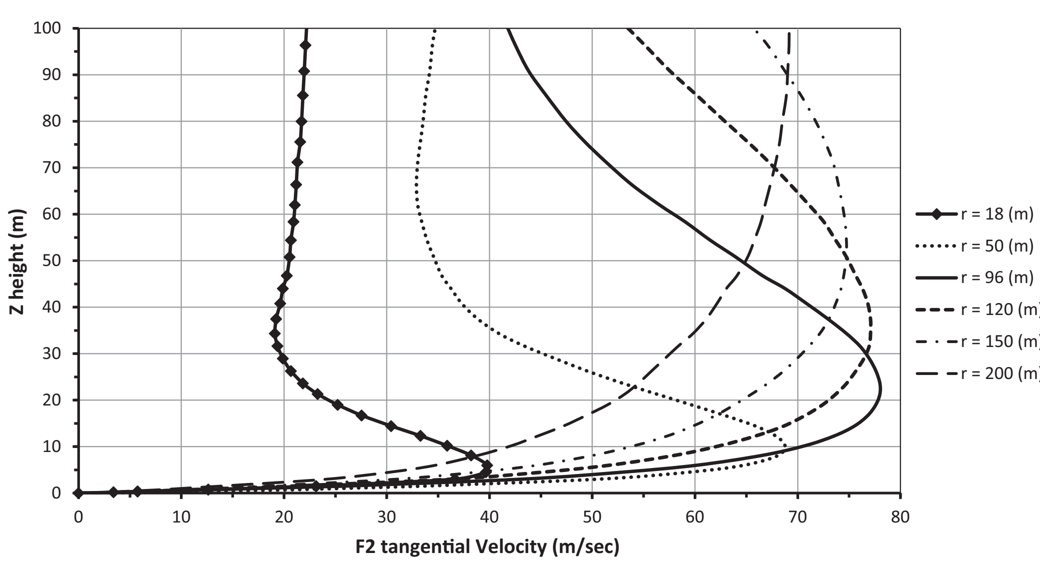


**Fig. 1.** Vertical profile of F2 tornado tangential velocity component for different radial distances "*r*" from tornado center.

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