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Behaviour of Transmission Lines under Tornadoes Based on WindEEE Testing

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ABSTRACT

This study reports an aeroelastic test to assess the dynamic response of a transmission line model under laboratory simulated tornado wind fields. The aeroelastic model is developed using a geometric scale of 1:65 and tested under scaled-down tornadoes in the Wind Engineering, Energy and Environment (WindEEE) Research Institute. The simulated tornadoes have a similar length scale of 1:65 compared to the full-scale. Such aeroelastic testing of transmission lines under laboratory simulated tornadoes is not reported in the literature. A multiaxial load cell is mounted underneath the model to measure the forces and moments in three perpendicular directions. A three-axis accelerometer is mounted to the model to measure natural frequencies using a free-vibration test. Radial, tangential and axial velocity components of the tornado wind field are measured using cobra probes. The structural responses of the aeroelastic model in terms of base shears are measured. The results of this study are utilized to understand the response of transmission lines to tornado-induced loads.

1. INTRODUCTION

High intensity wind (HIW) events in the form of tornadoes and downbursts cause more than 80% of weather-related transmission line failures (ASCE 2010, Dempsey and White 1996). However, the current manuals of practice and design guidelines are only based on the loads resulting from conventional atmospheric boundary layer wind profiles, not accounting for the loads coming from HIW events. Tornadoes are rated by the damage-based Fujita (F-scale), (Fujita and Pearson 1973) which is scaled from 0 to 5, providing an increasing degree of damage, path width and wind speed.

Computational Fluid Dynamics (CFD) can provide a good representation of the tornado flow field near the ground. Harlow and Stein (1974) developed the first numerical model to simulate the tornado flow field in a Ward-type domain. Lewellen et al. (1997) and Lewellen et al. (2000) modelled full-scale tornadic flow in a large domain using Large

Eddy Simulations (LES) and analyzed the flow features near the ground. Using the Reynolds Stress Model (RSM) turbulence closure, a CFD flow field of tornado-like vortices was developed by Hangan and Kim (2008). The steady-state wind field was obtained by solving three-dimensional Reynolds-Averaged Navier-Stokes (RANS) equations. El Damatty et al. (2018) developed a CFD simulation of a case study F2 full-scale tornado flow field incorporated into transmission line structures using an in-house non-linear finite element model to characterize the TL's overall behaviour under the tornado. Consequently, peak internal forces in the tower members were identified and compared with current design guidelines.

Laboratory simulations of tornado-like vortices have been developed to qualify the characteristics of this phenomenon. The first major laboratory simulation (Ward, 1972) led to the development of the Ward-type simulator. This simulator has a fan at the top to generate updraft and guide-vanes near the floor to provide angular momentum. Its improvement over time led to the creation of Tornado Vortex Chambers (TVC), which provide a good simulation of the characteristics inside a tornado (Davies-Jones 1973, Church et al. 1977, Baker and Church 1979, Rotunno 1979, Lund and Snow 1993, Wang et al. 2001, Sarkar et al. 2005, and Refan and Hangan 2012).

Regarding the investigation of the behaviour of transmission lines under tornado-induced loads, a few attempts have been made in the literature. The Effect of tornado loading on transmission line systems was examined by Savory et al. (2001). They used a simplified numerical tornado simulation and a linear finite element modelling of the towers. Hamada et al. (2010), and Hamada and El Damatty (2011 and 2014) developed an in-house nonlinear finite element numerical code, where all components of the tower and the attached conductors were simulated. The method can provide a full nonlinear three-dimensional finite element modelling of a whole transmission line system for both guyed and self-supported towers. The wind field developed by Hangan and Kim (2008) was incorporated into this numerical model. A procedure for the evaluation of the aerodynamic forces associated with the tangential, radial and vertical components of the tornado wind field was presented. The research introduced the concept of the extensive parametric study, which is necessary to obtain the peak internal forces developing in the members of a transmission tower. The parametric study was done by changing the tornado location relative to the studied tower. Therefore, each tornado location corresponds to a specific tornado configuration, resulting in a different set of loads on the tower and the conductors. The peak internal forces in the tower members obtained from the entire parametric study were identified together with the critical tornado configurations that correspond to those peak values. Hamada and El Damatty (2011) used this model to assess the behaviour of guyed transmission line structures under tornadoes, subsequently, Altalmas et al. (2012) conducted a similar study on self-supported transmission line structures under tornadoes. An aeroelastic model of a transmission line system consisting of five towers and 4 spans was developed by Hamada et al. (2017), which was used to investigate the response of transmission line systems under boundary layer wind. Load cases representing the critical effect of tornadoes on generic transmission line structures were then developed by El Damatty and Hamada (2016) and subsequently simplified by El Damatty et al. (2015).

The overall objective of this paper is to investigate the structural response of an aeroelastic multi-span self-supported transmission line under laboratory simulated tornadoes that are developed at the WindEEE research institute. The measured responses are in terms of base shears in two perpendicular directions.

2. WINDEEE RESEARCH INSTITUTE

WindEEE research institute facility, recently built at Western Univeristy, London, Ontario, Canada, provides a unique opportunity for conducting comprehensive research to assess the response of structures under tornado and downburst events. WindEEE is a three-dimensional wind-testing chamber with a hexagon shape. The testing chamber is 25 m in diameter and 4 m in height. It has more than 120 fans that are distributed along its perimeter and its ceiling, allowing the generation of various types of wind events, including tornadoes. Figure 1 shows a schematic view of the tornado generation in WindEEE. More details regarding WindEEE are provided by Hangan (2014).

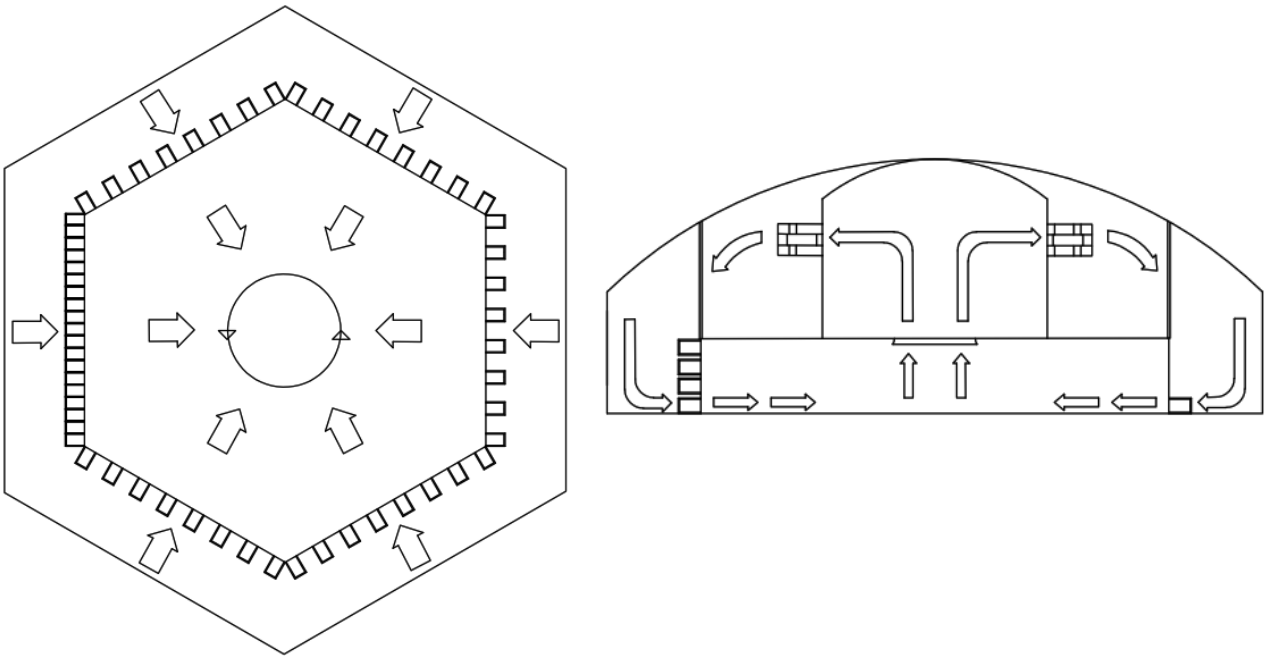


Figure 1. Tornado generation mechanism at WindEEE

3. TRANSMISSION LINE MODEL AND INSTRUMENTATION

In the current study, a multi-span aeroelastic self-supported transmission line model with a geometric scale of 1:65 is designed to simulate the static and dynamic behaviour of the full-scale prototype. Froude scaling is satisfied when accounting for gravitational forces and fluid-structure interaction. The developed finite element model along with the information available in the literature are used as a benchmark for the scaled stiffness, natural frequency and mode shapes of the scaled model. The aeroelastic model is built using a three-dimensional printer. The full-scale tower is made of steel and the model is constructed of plastic material with a density of 1150 $\frac{Kg}{m^3}$, modulus of elasticity of 1650 *MPa* and tensile strength of 48 *MPa*. Therefore, to simulate the full-scale mass distribution along the height of the towers, lumped masses using brass cubes are designed and appropriately located. The design of the aeroelastic conductor assumes the case of unshielded wires, as recommended by ASCE-74 (2010), where the bundle of four wires is simulated using a single conductor and the cable sag ratio is maintained throughout the test. An equivalent diameter of aircraft cables is used to provide the required mass for the scaled bundle and ion order to satisfy the aerodynamic requirements of the prototype bundle. Additional cylindrical foam bullets are attached to the cables at discrete locations along the cable's length.

The base shears are measured using a multi-axis load cell. Measurement of velocities and turbulence characterizations of the tornado wind fields performed using 8 cobra probes, split into two columns of 4 cobra probes where each is placed at mid-span of the model to measure the radial and tangential velocities of the tornado. Figure 2 shows the model details along with the cobra probes configuration.

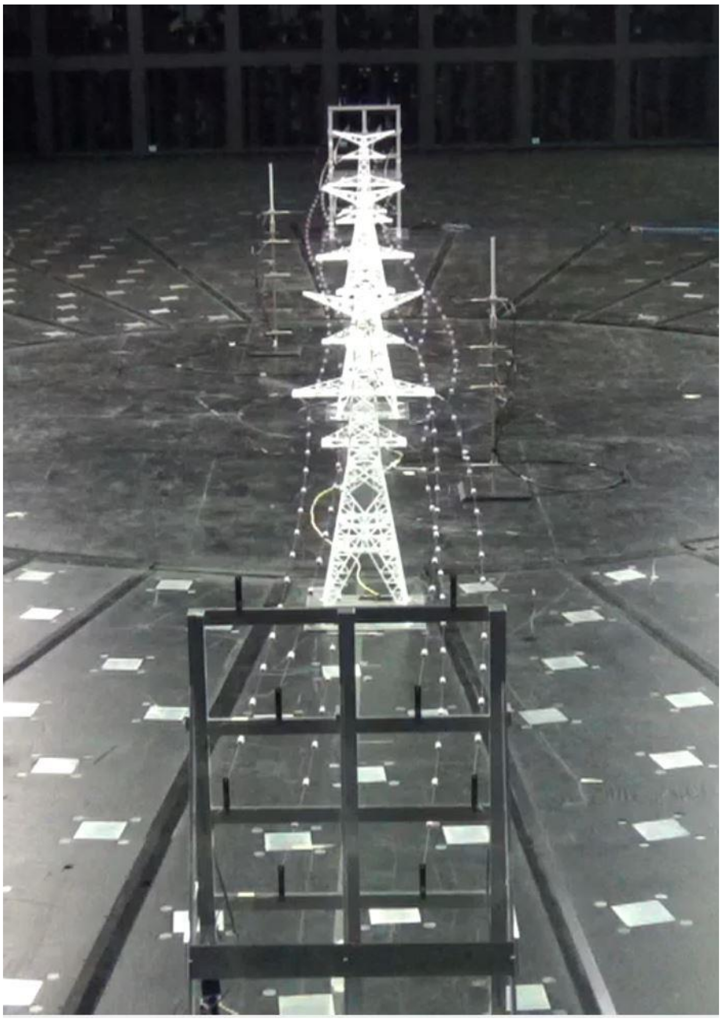


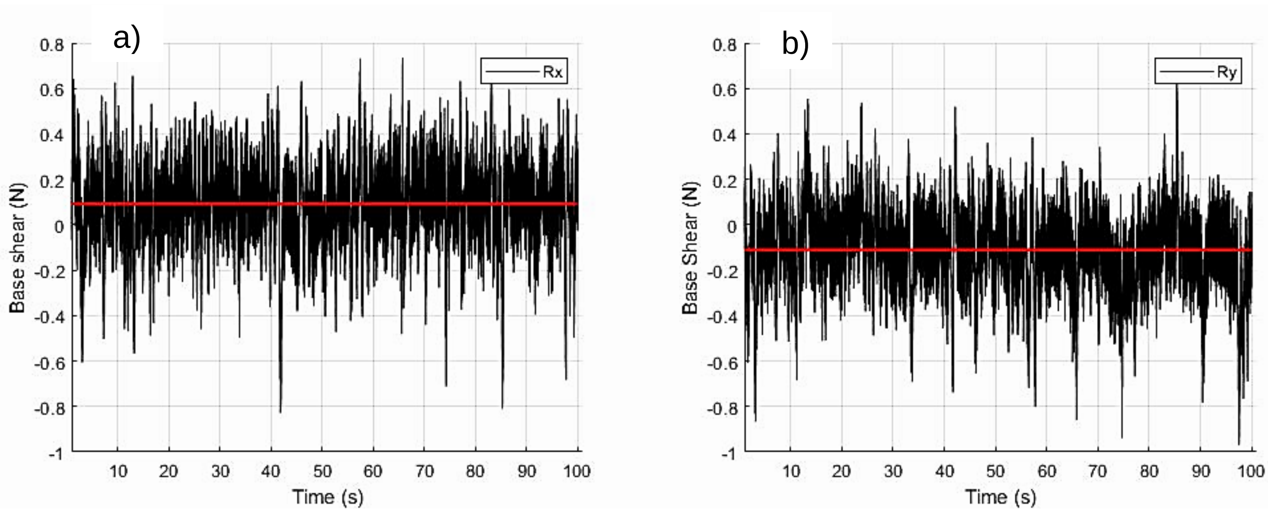
Figure 2. Transmission line model and cobra probes arrangement during the tornado

The location of the tornado, relative to the centre of the transmission tower, varies to assess the impact of several ranges of stationary tornado-induced loads on the structural response. Figure 3 shows the model tested under the 1:65 scaled tornado where the centre of the tornado interacts with the middle tower model. At each tornado location, the tower will experience different wind velocities and profiles.

Figure 3. Tornado simulation where it hits the middle tower

4. RESULTS AND DISCUSSION

The time histories of structural responses in terms of base shears, using a multi-axial load cell, are obtained. Base shears are measured in two perpendicular directions to the line model, where X is transverse to the direction of the line and Y is along the direction of the line. Since the time histories of base shear responses are found to be stationary, the separation of the mean from fluctuations is valid. Figure 4 shows the structural response in the form of base shear time histories for the tower of interest (the middle tower) in both the X and Y directions.



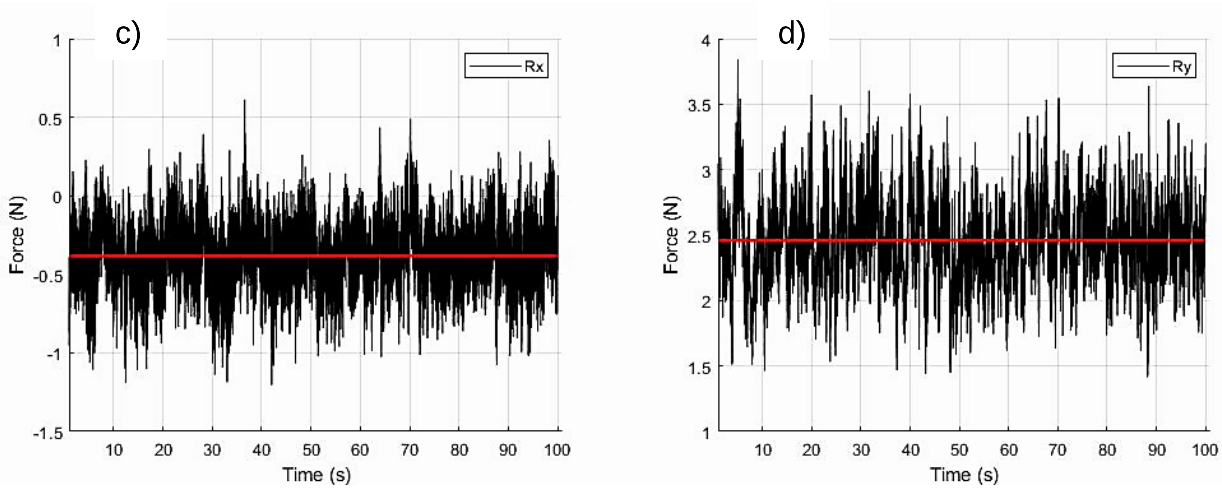


Figure 4. Response of the tower of interest in terms of base shears in X and Y directions where the tornado centre is at a,b) r=0.0 m and c,d) r=1.2 m with respect to the tower of interest

As shown in Figure 4, the tower of interest experiences different tornado-induced loads when the location of the tornado changes. The absolute mean value of the base shear in the X and Y directions where the tornado located at r = 0.0 m are 0.08 N and 0.10 N, respectively. The measured absolute mean values in the X and Y directions for the case of r = 1.2 m are 0.39 N and 2.44 N, respectively.

Considering the force scale of 1:274,625, the mean values represent 21.97 kN and 27.46 kN for the case of r=0.0 m, and 107.10 kN and 670.08 kN for the case of r = 78.0 m in full scale.

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