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Aeroelastic Testing to Examine the Dynamic Behavior of a Single Self-Supported Electrical Transmission Tower Subjected to Downburst Wind Loads

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ABSTRACT: Electrical transmission towers are an integral part of the power distribution system globally. Previous studies have shown that they can be vulnerable to high intensity non-synoptic wind events such as downbursts. This paper studies and compares the dynamic response of a single self-supported transmission tower to downburst and synoptic atmospheric boundary layer (ABL) winds. Wind tests were carried out using the downburst simulator at the NSF-NHERI Wall of Wind Experimental Facility on an aeroelastic model. Both downburst and synoptic ABL simulations have a similar wind speed at 1/5th of tower height and tower height respectively. The results indicate that dynamic response of a self-supporting tower can be slightly higher under downburst wind loads in comparison to synoptic ABL wind loads. Also, the results indicate mostly similar drag coefficients under downburst winds and synoptic ABL winds.

KEYWORDS: Transmission tower, downburst, aeroelastic modeling, wind tunnel testing, dynamic behavior, high-intensity winds, drag coefficient

1 INTRODUCTION

Energy, especially electricity has become a basic human need. Overhead high voltage transmission lines (TLs) are more common than the underground TLs in the US. The overhead TLs comprises supporting towers, conductors, insulators, and ground wires. A shortfall of electricity supply can have both social and economic implications for any community, as evidenced by the billions in dollars of losses associated with the 2021 Texas power outages (J. W. Busby et. al. 2021). Transmission towers are usually designed to resist environmental loads such as wind. However, spatially and temporally localized high-intensity wind events such as downbursts occur frequently and continue to impact the electrical power transmission infrastructure, leading to single or progressive tower collapse and power outages in various communities (A. Shehata and A. El Damatty, 2022). Preventing damages to TLs due to downbursts is particularly important given the current global rise in rapidly intensifying windstorms.

Downburst are non-synoptic wind events which differ from the synoptic/usual atmospheric boundary layer (ABL) winds as it has non-stationary flow characteristics (Orwig and Schroeder, 2007), shorter duration and its maximum wind speed occurs closer to the ground. This peculiarity has made the analysis of structural loads under downburst winds a difficulty, and many wind load provisions unsuitable for analyzing downburst loads on transmission towers. While the new ASCE, 74 (2020) guidelines for electrical transmission line structural loading have some recommendation for downburst loading, more research is necessary to examine their suitability to capture the complex dynamic response of different TLs and to increase the resilience of overhead transmission line systems, especially with the expected increase in extreme weather events.

To better understand the dynamics of transmission towers subjected to downburst wind loads, researchers have used both experimental (Elawady et al. 2017) and numerical (A. Y. Shehata et al., 2005; Aboshosha and El Damatty, 2015) methods, as full-scale data collection can be difficult (Aboshosha et al. 2016). Experimental simulations of downbursts have used the impinging jet method (Chay and Letchford, 2002; Elawady et al., 2017) and flow redirection method (Butler and Kareem, 2007; Le and Caracoglia, 2019). However, transmission line systems have not been experimentally evaluated in flow-redirected simulations of downburst events, probably due to the 2-dimensional nature of the flows generated by this method and small scale of the currently available simulators.

Drag and shielding coefficients of downburst winds on lattice structures have not been estimated either numerically or experimentally, but previous studies have relied on the coefficients from synoptic wind simulations. The higher vertical component of downburst winds could influence these factors. The variability in the height of peak downburst wind speeds above the ground, and its effects on TLs have also not been previously investigated. While this variation might not have significant effect on the entire TLs, it might have an influence on the response of a single tower during the construction phase. All these parameters are important in effectively predicting the response of the TLs under downburst wind loads and need to be investigated.

To this end, an aeroelastic experimental study is ongoing at the newly constructed downburst simulator of US National Science Foundation (NSF)-Natural Hazard Engineering Research Infrastructure (NHERI) Wall of Wind (WOW) Experimental Facility (EF) at Florida International University (FIU) aiming at advancing the knowledge on the dynamic behavior of electrical power transmission infrastructure during downburst events. The downburst testbed at the NHERI WOW EF simulates a two-dimensional gust front flow of downbursts. The produced horizontal velocity profile compares well with the existing field and other laboratory simulated downbursts. The second section of this paper explains the methodology and the simulator used in this study. The results are analyzed and discussed in the third section while the fourth section gives the conclusion of the current study.

2 METHODOLOGY

2.1 *Downburst Simulator and Experimental Protocol*

As mentioned earlier, the experimental study was carried out at the NHERI WOW EF. The WOW EF is an open jet wind tunnel with a 2 x 6 array of fans. The facility is capable of testing large and full scale models up to and at category 5 hurricane wind speeds of ~70m/s (Gan Chowdhury et al. 2017). The downburst simulator at the facility is a wind re-direction device attached to the outlet of the flow management box of the WOW EF. The device has two slots at the lower part which open and close to create the downdraft of the downburst. Figure 1 shows the downburst simulator while Figure 2 shows a typical wind velocity time history and the turbulence intensity. The turbulence intensity is calculated with Equation 1 (Solari et al. 2015).

$$I_{u,t} = \frac{\sigma_{u'(t)}}{\bar{U}_{(t)}} \quad (1)$$

Where, $\sigma_{u'}$ is the slowly-varying standard deviation of residual turbulent fluctuating velocity and $\bar{U}_{(t)}$ is the slowly-varying mean velocity.

In comparing synoptic ABL and downburst wind effects on structures, two approaches can be followed:(i) Comparing events where the peak wind velocity at the downburst nose match the wind velocity at tower height and (ii) Comparing events where the wind velocity at tower heights under both downburst and synoptic ABL match. The first approach was used in this study.

The tests were run from 0° to 90° wind attack angle at 15° increments, and 8.1 m/s, 9.2 m/s, 10.5 m/s and 13 m/s as maximum radial wind velocity at 1/5th of the tower height. These wind velocities correspond to the mean wind velocities at tower heights in the synoptic ABL tests by Azzi et al. (2021). Wind speed and turbulence characteristic measurements at the center of the turntable were measured with Cobra probes sampled at 2500Hz.

Figures 2(a), 3(a) and 3(b) shows the time history of the velocity, strains and accelerations with peak zones indicated in the middle of the time series. It is important to note that the peak zone limits from the time history of the velocity, strains and accelerations were calculated using the detection of change-point approach (Lavielle, 2005 and Romanic et al. 2019).

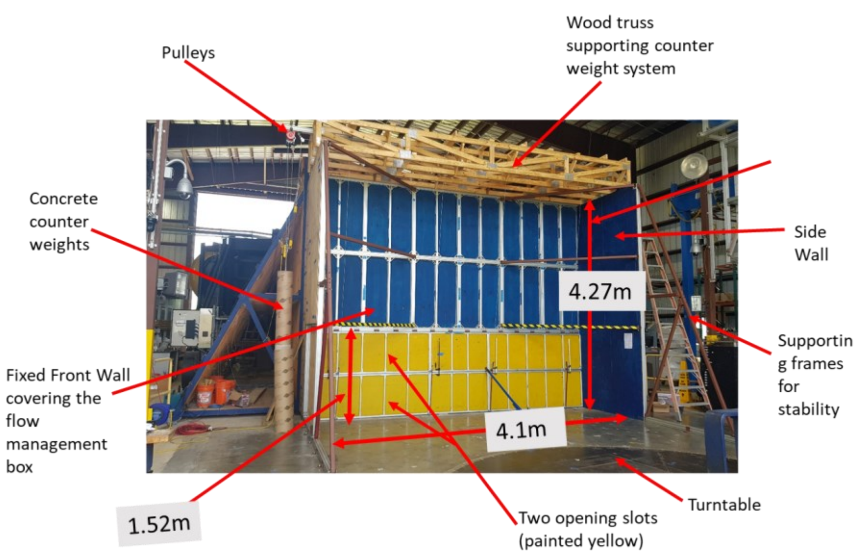
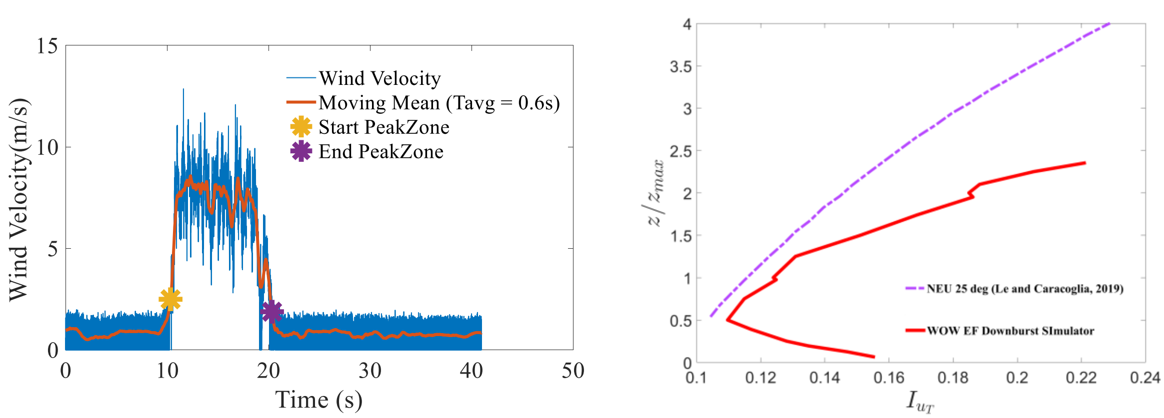
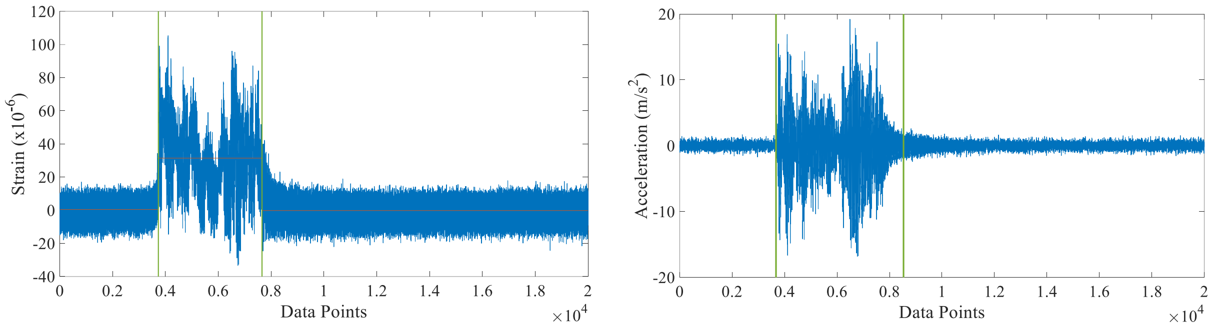


Figure 1. Downburst simulator at WOW EF



(a) Time history of downburst (b) Turbulence intensity

Figure 2. Downburst flow



(a) Time history of strains (b) Time history of acceleration

Figure 3. Time history of strain and acceleration response indicating peak zones

2.2 *Transmission Tower and Instrumentation*

The transmission tower used in this study is a self-supporting tower. Details of the modeling can be found in the study by Azzi et al. (2021). The length scale was 1:50. The aeroelastic tower has a single spine designed to replicate the dynamic properties of a full-scale tower surrounded with a cladding. Three accelerometers, six strain gauges and one load cell were attached to the model tower, and these were sampled at 500 Hz. The orientation of the tower with respect to the wind direction is shown in Figure 4, while Figure 5 shows the location of the instruments on the tower. Figure 6 depicts the vertical profile of the downburst and synoptic ABL horizontal wind velocities and turbulence intensities at turn table center.

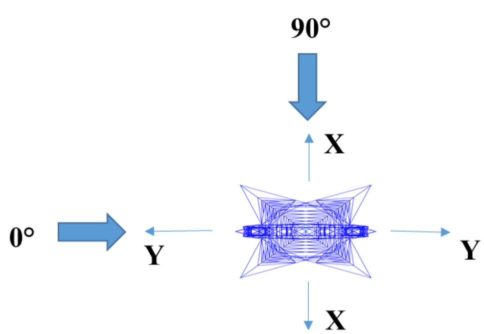


Figure 4. Wind direction and tower axis

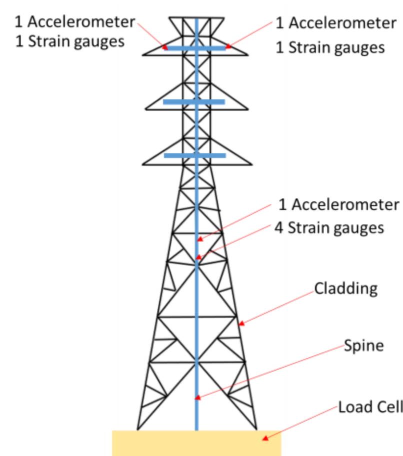
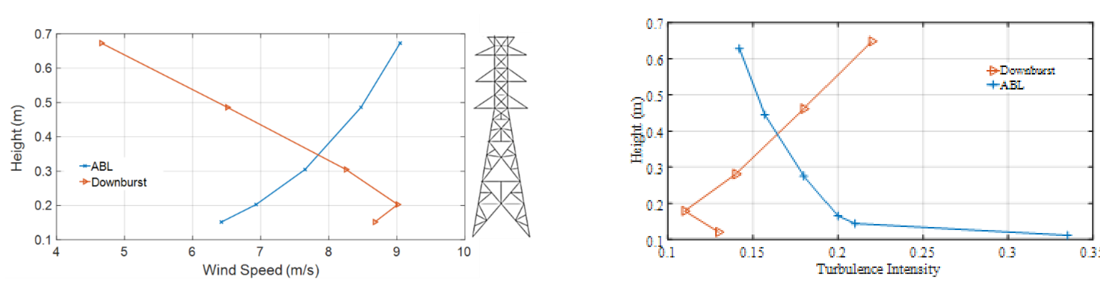


Figure 5. Transmission tower and instrumentation



(a) Wind velocity (b) Turbulence intensity

Figure 6. Vertical wind profile of ABL and downburst winds at 9.2 m/s max wind velocity

3 RESULTS AND DISCUSSION

3.1 Base Shear Forces and Moments

The time histories of the along wind force and base moments of the tower under downburst (DB) and synoptic ABL winds at 90° wind attack angle and 9 m/s case are presented in Figure 7. The time history shows a rapid increase in base shear and moments that coincide with the sharp increase in wind speed observed in the velocity time history of downburst wind (see Figure 2(a)). This was observed in all the downburst simulations for other wind speeds and wind directions.

The peak base moments during the downburst tests were only higher than the synoptic ABL tests in the weak axis (i.e., y-axis), with the critical wind attack angles of 30° and 45°. Other studies including Elawady and El Damatty (2016) have shown the oblique wind direction to be a critical case in the presence of conductors.

3.2 Tower Top Acceleration

The root-mean-square (rms) of accelerations on the tower top (cross arms) under downburst and synoptic ABL wind is presented in Figure 8. These rms calculations for the downburst event were based on the tower accelerations within the peak zone as indicated in Figure 3(b). Current results show a higher acceleration rms under downburst wind loads in comparison to synoptic ABL wind loads at 0° and 90° wind direction.

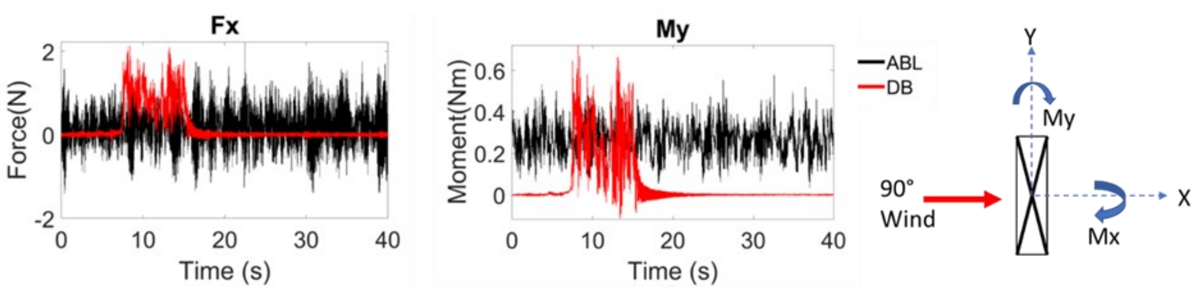


Figure 7. Base shear and base moments of tower under downburst (DB) and synoptic ABL at 9.2m/s max velocity along tower height with wind along 90° (weak axis)

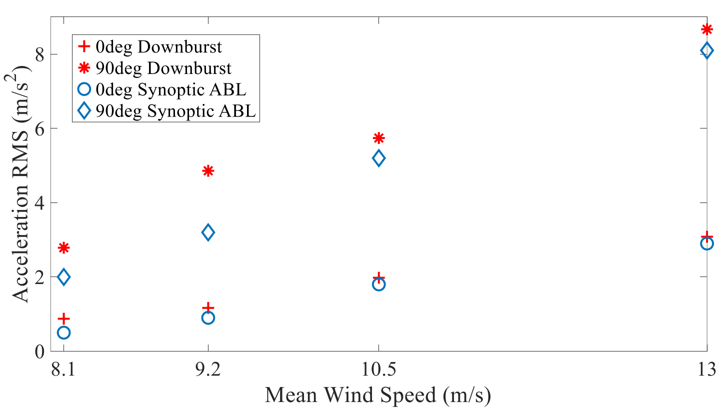


Figure 8. Acceleration rms of tower top under ABL and downburst wind loads

3.3 Mean Drag Coefficient

The drag coefficient was calculated using the measured strain from the strain gauges attached to the spine of the tower model. The calculation is based on Equation 2 (Azzi et al. 2021).

$$C_D = \frac{4.\varepsilon.E.I}{b.\rho.\sum_{i=1}^{5} A_i.U_i^2 \cdot d_i} \quad (2)$$

Where ε is the mean strain within the peak zone in the direction of the loading, E is the modulus of elasticity of the spine, I is the moment of inertia of the section about the axis of bending, b is the distance to the centroid, ρ is the density of air, A_i is the area of the elements of the tower in the plane perpendicular to the wind direction of zone i, d_i is the distance from the strain gauge to the point of application of the force on zone i and U_i is the mean velocity within the peak zone at the height of zone i. Details of the tower zoning are fully explained in Azzi et al. (2021).

Figure 9 shows the results of the analysis with comparison with the drag coefficient under synoptic ABL winds. The drag coefficients under downburst wind loads are similar in comparison to the ABL values especially at 0° and 90° wind direction where the values are the same. It is important to note that if the maximum of the moving mean strain values are used in this analysis, the drag coefficients would be higher than those shown in Figure 9.

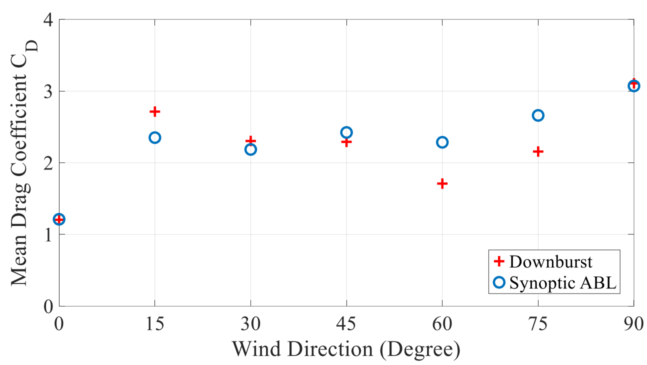


Figure 9. Mean drag coefficient of tower under ABL and downburst at 9.2m/s max wind speed along height

4 CONCLUSION

The current study on a self-supported aeroelastic lattice transmission tower has compared the tower response given a matching wind velocity at tower height under ABL winds and 1/5th tower height under downburst winds. While there is no generally accepted convention for this comparison and given the non-stationarity of downburst events, this study has used mean values within the peak zones.

The study has shown that the dynamic response of a self-supporting tower can be slightly higher under downburst wind loads in comparison to synoptic ABL wind loads. Mean drag coefficients of the single self-supported transmission tower were mostly similar under downburst wind loads in comparison to synoptic ABL.

However, more assessment of the adequacy of the quasi-steady data analysis applied on tower response data under downburst winds is needed. It would also be important to assess the buffeting response, vortex-shedding induced dynamic response and the resulting dynamic amplification factors (DAFs) in both cross and along wind directions. A framework for comparing wind loads on lattice structures in downburst and synoptic ABL requires further attention.

More tests are planned at the WOW EF for single towers and TLs under downburst loads to consider effects of varying height of peak downburst wind speeds on tower response.

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