RESILIENT INFRASTRUCTURE
June 1–4, 2016

WIND TUNNEL TESTING OF A MULTIPLE SPAN AEROELASTIC TRANSMISSION LINE SUBJECTED TO DOWNBURST WIND

Amal Elawady
Western University, Canada

Haitham Aboshosha
Western University, Canada

Ashraf El Damatty
Western University, Canada

Girma Bitsuamlak
Western University, Canada

ABSTRACT

A 1:50 scale aeroelastic wind tunnel test for a multi-span transmission line system is conducted at the WindEEE dome under downburst wind. WindEEE is a novel three-dimensional wind testing facility capable of simulating downbursts and tornadoes. This test simulates a transmission line consisting of v-shaped guyed towers holding three conductor bundles. Details about the model design, the wind field and the test setup are provided. A downburst loading case that is critical for the line design and causes unbalanced tension load on the conductors is investigated in the current study. Resulting line responses obtained from the test are compared with a previously developed finite element model by the research group at the University of Western Ontario. The comparison shows a good agreement which validates the finite element models. Results obtained from this test will be very useful to understand the behavior of the lines under downburst wind.

Keywords: Aeroelastic modeling, Downburst, Transmission line, Wind load, High Intensity Wind (HIW).

1. INTRODUCTION

Fujita (1985) defined a downburst as a severe descending mass of cold air that impinges on the ground and then convects radially. Different design guidelines such as the CIGRE (2009) have highlighted that downbursts are responsible for more than 80% of the weather-related failures of transmission lines worldwide. Examples of the previous failures under downburst include failure of 18 (500 kV) and 57 (110 kV) transmission towers during 2005 (Zhang 2006), as well as failures of guyed towers belonging to Manitoba Hydro and Hydro One during 1996 and 2006, respectively (McCarthy and Melsness 1996; Hydro One 2006).

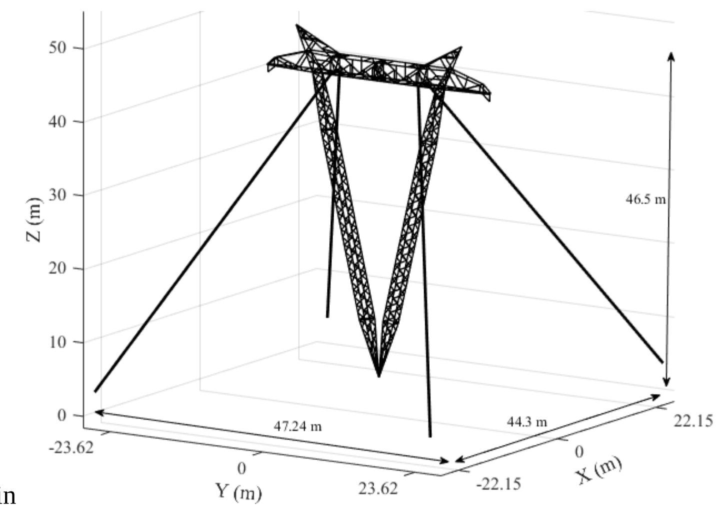
Despite those failures, most design codes of transmission lines account for wind loads due to synoptic wind but not due to downburst wind. This encouraged several researchers, including many from the University of Western Ontario, to study the effect of downbursts on transmission lines. For example, Shehata et al. (2005) and Shehata and El Damatty (2007) studied the behavior of a guyed transmission line and showed that the main challenge of analyzing the line under downburst wind is the localized nature of the downburst. Such localized nature results from the scale of the event (i.e. ~500-1000 m diameter) which is comparable to the span length of the line. This comparable scale leads to altering downburst loads applying on the line with the change of the downburst location. Downburst locations leading to critical loads have been identified by Shehata and El Damatty (2007), Shehata et al. (2008), El Damatty and Aboshosha (2012) and El Damatty and Elawady (2015). Those studies showed that three downburst locations can be critical for the line design. The most critical location is when downburst acts at an oblique location to the tower of interest leading to loads on conductors at one side of the tower. This causes an unbalanced conductor tension and ultimately high longitudinal forces on the tower.

It worth mentioning that most of the available studies in the literature were conducted using numerically simulated downburst wind field and employing Finite Element Models for the transmission line. In the current study, an aeroelastic wind tunnel test for a multi-span transmission line subjected to downburst wind is conducted. This is to assess the findings obtained from previous numerical studies and to understand the interaction between downburst and the line. The test is conducted at the WindEEE dome, the new three dimensional wind tunnel testing facility at the University of Western Ontario that is capable of simulating downburst and tornadoes. The critical downburst case of loading that causes unbalanced conductor tension and high longitudinal tower forces is investigated in this paper in detail.

2. AEROELASTIC WIND TUNEL TESTING

In this section a description of the prototype line as well as the designed aeroelastic model is provided.

2.1 Full-scale transmission line system



The transmission line, shown in Figure 1, (Tangent line, 500 kV single circuit tower) is chosen for the test. The line consists of guyed towers supported by 4 guys at the height of 40.72 m above the foundation level. The towers have two horizontal cross arms protruded from the tower shaft at the level of 40.72 above the foundation level (main girder level) in the transverse direction and ended at the location of the insulator. Three conductor bundles are attached to the tower through the insulators; two at the tip of each cross arm and one at the center point of the main girder. Each conductor bundle has 4-wires and each wire has a diameter of 0.02159 m, which weights 8.67 N/m. The conductor bundles have a square shape with a separation of 0.48 m. The bundles are supported by insulators with a length of 4.27 m. A conductor span of 125 m and sag at the mid-span of 3.25 m are considered in the model. Although the span length for such towers is typically longer, the considered 125 m represents .is till practical and used in some cases. Galvanised steel guy wires of a 0.019 m diameter and 50 m length are used to prevent the displacement at the anchorage level. A pretension force of 11 kN is applied to all guys. The tower is resting on the ground on a pivotal (i.e. hinged) support that allows for the rotations at the tower centre. The total weights approximately six tons and has a height of 46.5 m.

2.2 Aeroelastic modelling of the line

An aeroelastic scaling of a structure must consider a geometric scaling of the exterior dimensions and corresponding scaling of all forces influencing its structural behavior. This means scaling of elastic, inertia, viscous and gravity forces and damping forces. Maintaining the geometry is crucial for the aerodynamic loads, while maintaining the stiffness and mass is crucial for the dynamic inertial loads associated with the model response.

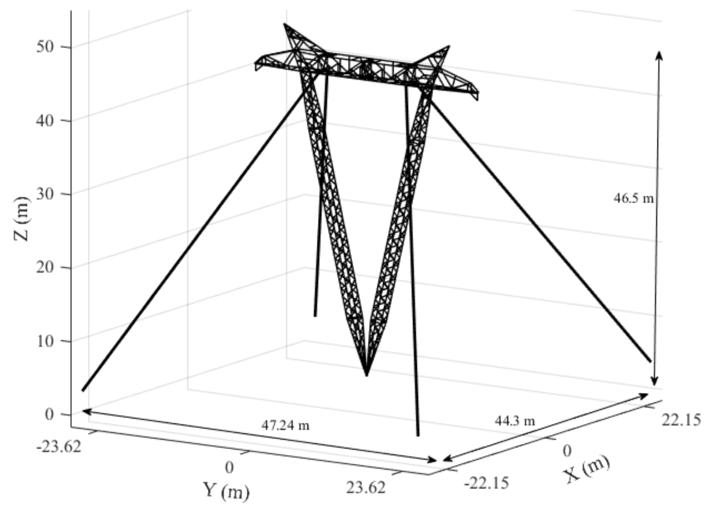


Figure 1: Three dimensional view of the tower "Z"

According to Isyumov (1972), it is preferred to use the prototype material to model the aeroelastic structure in order to maintain the structural damping where dynamic responses are pronounced. However, due to the light weight of the structure under this study, it is difficult to satisfy the mass scaling using the steel material. As such, aluminum is selected as an alternative to satisfy the mass scaling requirement.

A length scale of 1:50 is chosen for the model. Froude scale, which characterizes the ratio between inertial forces and gravitational forces, is maintained in the model as that in the prototype (Isyumov 1972). This is achieved by linking the velocity scale to the square root of the length scale (i.e. 1:7.07). The scaling ratios of all other variables are functions of the length and velocity scales and are summarized in Table 1.

Previous studies on downburst effect on transmission line structures showed that considering at least six spans (three on both sides of the tower of interest) is essential to predict the proper responses of the tower (Shehata et al. 2005, Aboshosha and El Damatty 2015). Similarly, six spans are considered in the aeroelastic model. Span length is chosen equal to 2.5 m in the model scale, which is equivalent to 125 m in the full scale. Although this is less than the typical span length used for such towers (i.e. ~200-500 m), it is still practical and represents the span used in some cases. Previous studies on downbursts (Aboshosha and El Damatty 2015, and El Damatty and Elawady 2015) showed that the ratio between the downburst diameter and the span length is a key parameter in characterizing peak loads transferred from the conductors to the towers. Such a ratio is maintained in the current test. The simulated downburst at WindEEE has a 3.2 m diameter and the modeled conductor span has a 2.5 m length leading to a ratio of 1.3. That ratio is compatible with the ratio found in typical full scale studies. For instance, a downburst with a diameter of 500-1000 m and a conductor span of 500 m, result in a ratio in the order of 1 to 2.

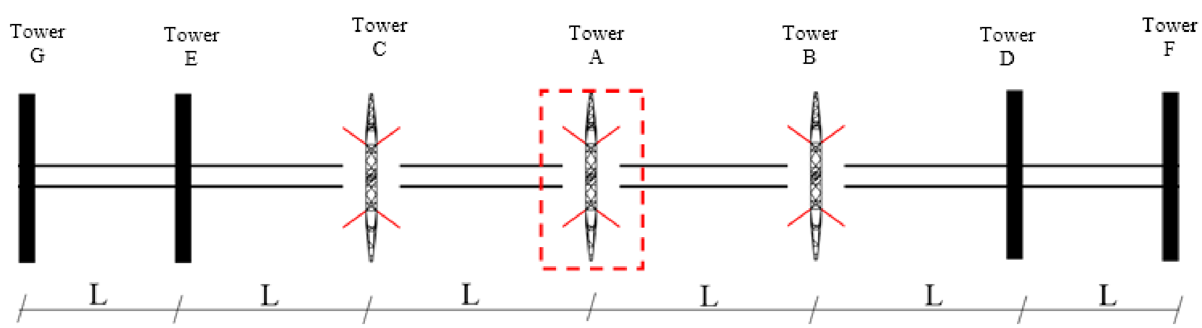


Figure 2 shows a layout for the tested transmission line. The tested line include three fully aeroelastic towers at the middle and four rigid frames at the two ends. Those rigid frames are used to support the conductors. Figure 3 shows a picture of the assembled line starting from the mid tower up to the end of the line, while Figures 4 show the aeroelastic towers and Figure 5 show the rigid towers. The aeroelastic towers consist of: (1) an aluminum spine that is designed to model lateral and torsional stiffness and (2) RP non-structural cladding attached to the spine and used to model the geometry of the tower angle members. Dimensions and cross sections of the aluminum spine are shown in Figure 6. As shown in the figure, cross section of the spine at the tower legs is chosen to be circular to avoid the discrepancies between the responses under different angles of attack (Kong et al. 2009). RP cladding is made out of segments and each is connected to the spine only at one point using an aluminum clamp to prevent their contribution to the tower stiffness. Conductor bundles are simulated using equivalent single steel wires with small bullets of foam as shown in Figure 3. Those bullets are carefully chosen to maintain the modeled wire drag area as the target drag area from the full-scale conductor bundle.

The guyed tower model is restrained at the base using: 1) a central hinged support which is modeled using universal joint as shown in Figure 7-a, and 2) four guys connected to leaf springs as shown in Figure 7-b. The leaf springs are carefully designed to model the proper flexibility of the guys. Conductors are supported by the towers using steel rods and are supported at the end to towers F and G using leaf springs as shown in Figure 7-c. Stiffness of those leaf springs is chosen to represent the effect of adjacent spans.

Table 1: Scaling ratio for various physical parameters of the model

Parameter	Scaling ratio
Length	$\lambda_L = L_m / L_p = 1{:}50$
Velocity	$\lambda_v = \lambda_L^{0.5} = V_m / V_p = 1{:}7.07$
Time	$\lambda_T = T_m / T_p = \lambda_L / \lambda_V = 1{:}7.07$
Density	$\lambda\rho = \rho_m / \rho_p = 1{:}1$
Mass per Unit Length	$\lambda_m = \lambda_\rho \lambda_L^2 = 1{:}2500$
Mass	$\lambda_M = \lambda_\rho \lambda_L^3 = 1{:}125{,}000$
Mass Moment of Inertia per Unit Length	$\lambda_i = \lambda_m \lambda_L^2 = 1{:}6{,}250{,}000$
Mass Moment of Inertia	$\lambda_I = \lambda_M \lambda_L^2 = 1{:}312{,}500{,}000$
Acceleration	$\lambda_a = a_m / a_p = \lambda_v / \lambda_T = 1{:}1$
Damping	$\lambda_\zeta = \zeta_m / \zeta_p = 1{:}1$
Elastic Stiffness	$\lambda_{EI} = \lambda_{GC} = \lambda_V^2 \lambda_L^4 = 312{,}500{,}000$
	$\lambda_{EA} = \lambda_V^2 \lambda_L^2 = 1{:}125{,}000$
Force per Unit Length	$\lambda_f = \lambda_V^2 \lambda_L = \lambda_L^3 / \lambda_T^2 = 1{:}2500$
Force	$\lambda_F = F_m / F_p = \lambda_V^2 \lambda_L^2 = 1{:}125{,}000$
Bending and Torsional Moment	$\lambda_{BM} = \lambda_V^2 \lambda_L^3 = 1{:}625{,}000$

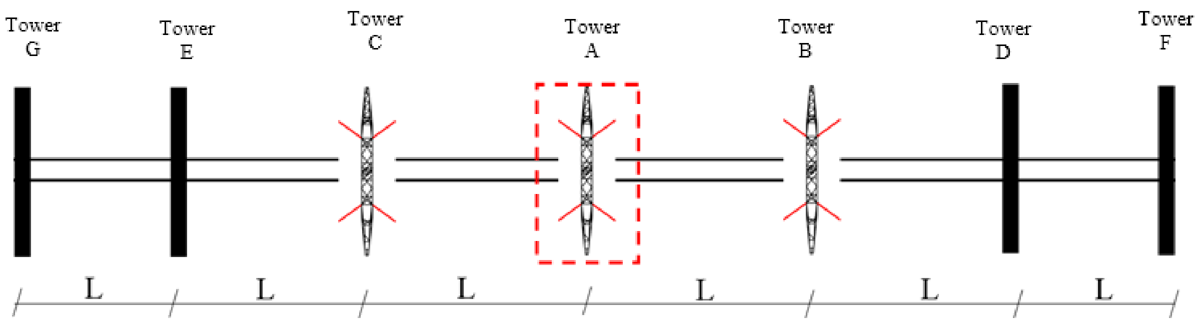


Figure 2: Schematic of the test layout and the names of the tested towers

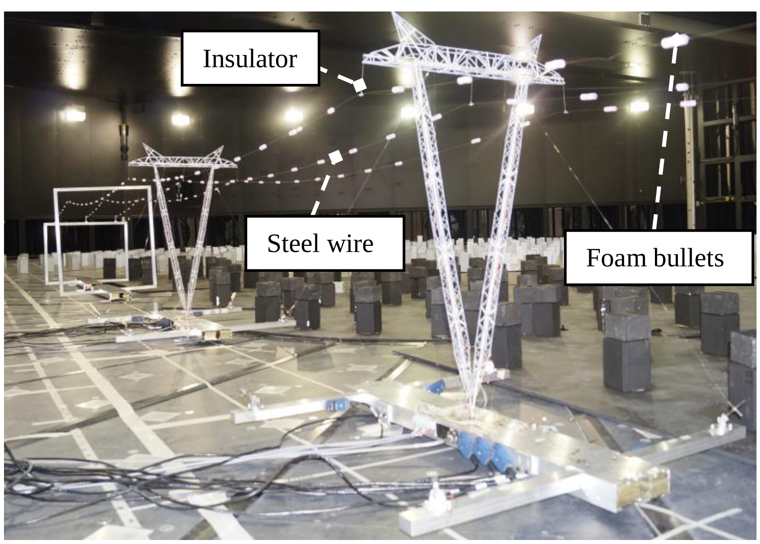


Figure 3: Half-length of the assembled line

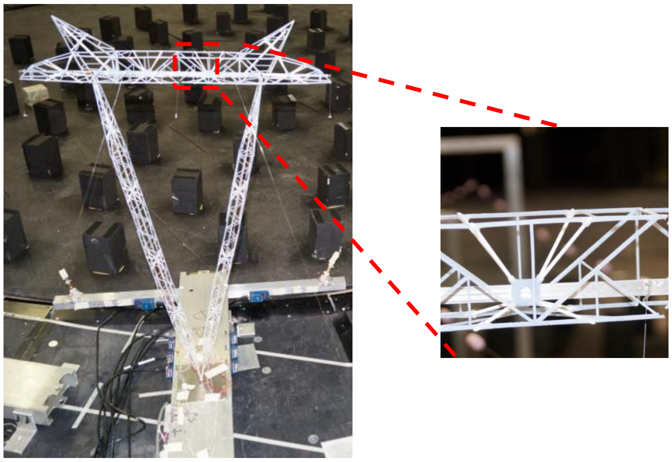


Figure 4: Test picture of A, B, and C towers

Figure 5: Test picture D, E, F, and G towers

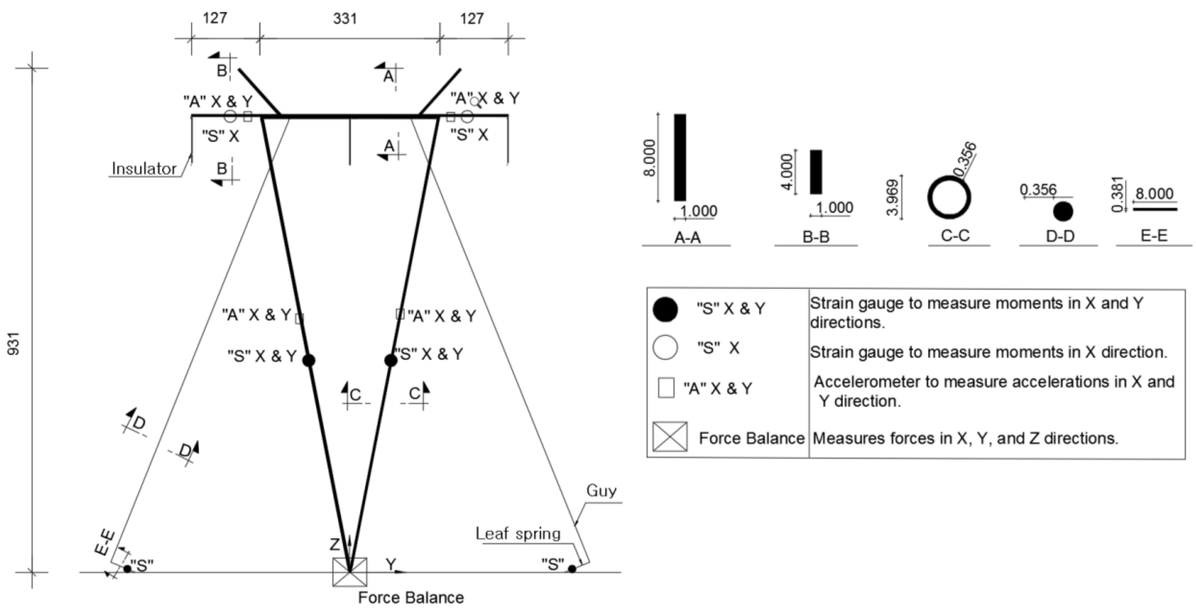
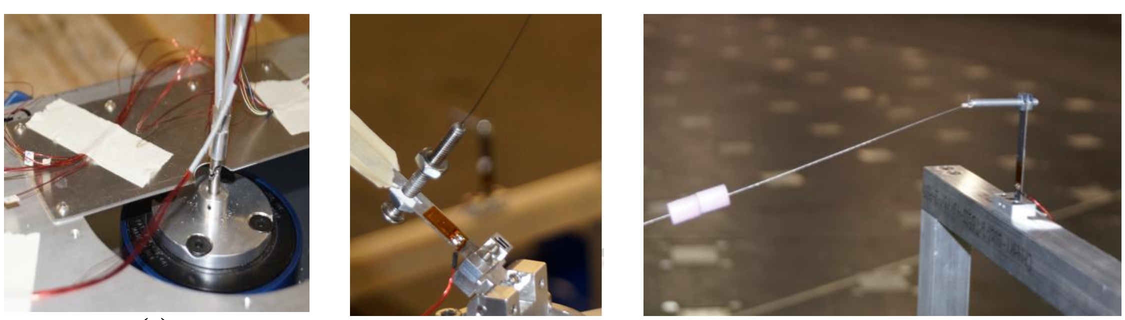


Figure 6: Spine dimensions and instrumentations of tower A, B, and C (all dimensions are in mm)



(a) (b) (c)

Figure 7: (a) 2-DOF Universal Base Support, (b) Supporting guy anchorage, (c) Conductor end support Instrumentations and data acquisition system

Different measurement instruments are used as shown in Figure 6. Those instruments include: strain gauges to measure in-plane (Y direction) and out-of-plane (X direction) bending moments in the cross arms and mid-height legs, strain gauges to measure the tension in the guys, force balances to measure the exerting base forces in three directions, and accelerometers to measure accelerations at main girder as well as mid-height legs. Figure 6 illustrates various measurement devices employed.

2.4 Downburst Wind Field at WindEEE

An attempt is conducted at the WindEEE dome to measure the wind field of the downburst before starting the test using cobra probes. A number of 12 Cobra Probes installed on two towers as shown in Figure 8 are used to measure the wind field. Figure 9 shows the testing chamber dimensions as well as the found three critical locations where the radial speed, V_{RD}, is maximum. A sample of the speed time history is shown in Figure 10, while the three maximum profiles are shown in Figure 11. Those maximum profiles are found at R/D ratio equals to 0.8, 0.9 and 1.0 where R is the radius measured from the downburst centre and D is the diameter of the downburst. The profile leading to the peak maximum radial velocity, V_{max}, is found at R/D =0.9 and is compared with the peak profile obtained from the CFD simulation (Aboshosha et al. 2015) as shown in Figure 12. As indicated from the figure, the two peak profiles are in a good agreement.

Figure 8: cobra probe devices

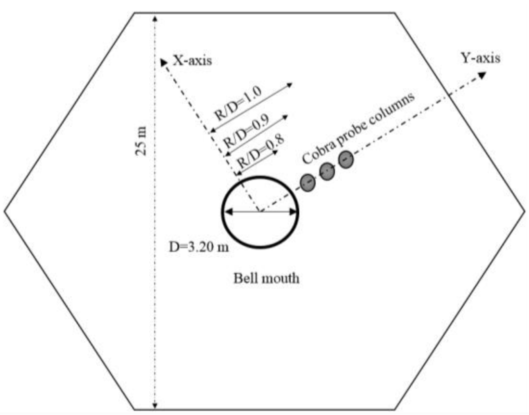


Figure 9: Cobra probe sample locations at WindEEE

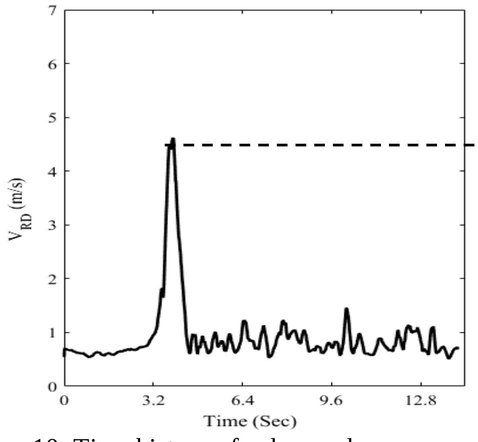


Figure 10: Time history of cobra probe measurement

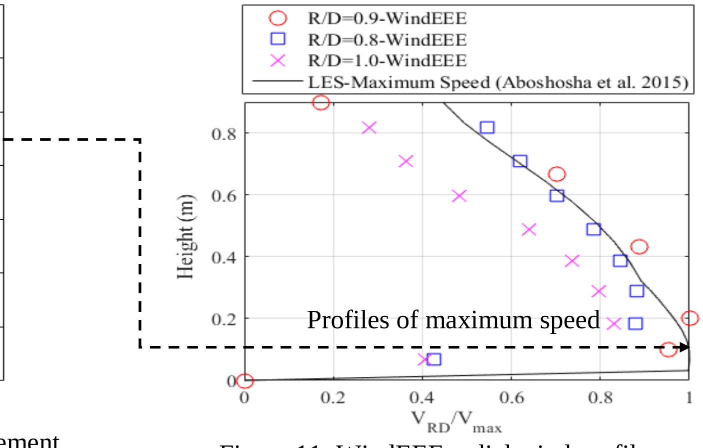


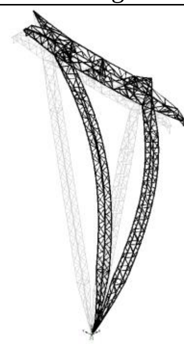
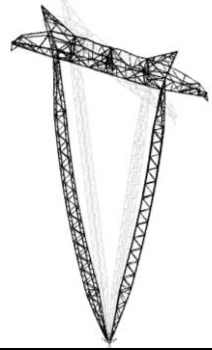
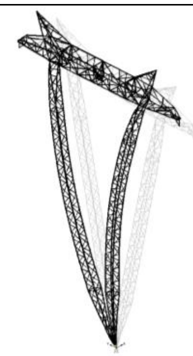
Figure 11: WindEEE radial wind profiles

3. VALIDATION OF THE AEROELASTIC MODEL DESIGN

A free vibration test is conducted to evaluate the natural frequencies of the model. Natural frequencies are obtained from the peaks in the power spectral density of the acceleration responses.

Table 2 shows the natural frequencies of the model compared with the target frequencies for the first three vibration modes. As indicated from the table, the model frequencies are in good agreement with the target frequencies with a maximum difference of 8%.

Table 2: Targeted and aeroelastic model modal results

			
Mode no.\ Description	Mode 1, Out-of-plane bending	Mode 2, Torsional	Mode 3, In-plane bending
Proto. Frequency (hz)	1.44	1.88	2.44
Model Frequency (hz)	10.15	13.3	17.3
Target Frequency (hz)	10.3	14.3	18.7
Difference	1.3 %	7.8 %	8.0 %

4. IN-HOUSE FINITE ELEMENT PROGRAME VALIDATION

The test is designed based on the findings of previous studies related to the critical configurations of the downburst (Sheta and El Damatty 2008, El Damatty and Aboshosha 2012; El Damatty and Elawady 2015). Those studies showed that the most critical case of loading is when the downburst acts at an oblique angle of attack to the tower of interest causing a non-symmetrical loading on the adjacent spans from each side. This causes unbalanced tension forces in the spans adjacent to the tower of interest which apply high longitudinal forces acting on the tower. This oblique load configuration is one of the major aspect that differentiate between the downburst and synoptic winds. The current study adopted the oblique load case to validate the numerical models.

El Damatty and Elawady (2015) has shown that the maximum tension force developing under the downburst oblique load case occurs when the projection of the center of the downburst on the line is located approximately on the second span from the tower of interest. In the current study, the tower is placed so that the projection of downburst center is located at distance X equal 1.25L, 1.5L, and 1.75L measured from the center of Tower B. The evaluation of the radial wind profiles of the downburst has shown that the maximum V_{RD} in the range of R/D equals 0.8 to 1.0. As such, the tower is assumed to be located at distance Y equal 2.56 m, 2.88 m and 3.2 m which represents R/D ratios of 0.8, 0.9, and 1.0, respectively. The combinations of variations of X and Y tested distances resulted in a number of nine locations of the tower B relative to the downburst center as shown in Figure 12. The figure shows the base shear results of the nine locations tested. The figure shows that the maximum base shear occurs at a distance X equal 3.125 m and Y equal 2.56 m. Out of the nine locations, the current study will utilize the test results of the critical configuration to validate the numerical models; i.e., at X equals 3.125 m and Y equals 2.56 m. A schematic plan view of the critical configuration of the downburst relative to the tower center is shown in Figure 13.

A sample of the time history responses of the tower is shown in Figure 14. The time variations of the response shows a sudden peak occurring and then decreasing suddenly till it reaches a minimum peak and then a stabilization occurs. The mean response is obtained out of the peak response by adopting a cutting off frequency equals twice the shedding frequency of the main vortices as recommended by Kim and Hangan (2007) and Aboshosha et al. (2015). The mean response is then compared to the numerical models solution (FEM).

Figure 15 shows the results of the comparison conducted between the numerical models solutions and the test measurements. The results show a good agreement between the test results and the numerical tools (FEM). The differences is equal to 12.3%, 9%, -15.4%, ±3.5% and 1.2% for the guy's tensions, base moments, base shears, mid height moments, and the cross arm moment, respectively.

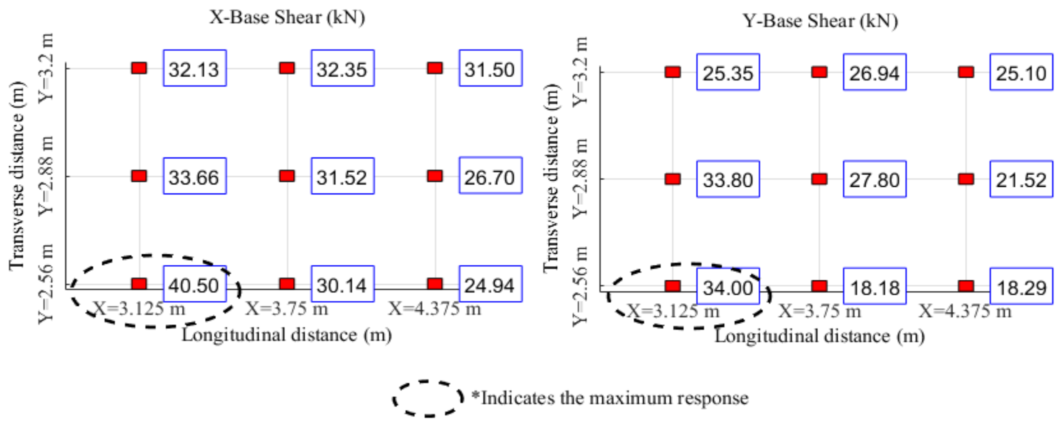


Figure 12: Base shear results of the oblique downburst configuration tests.

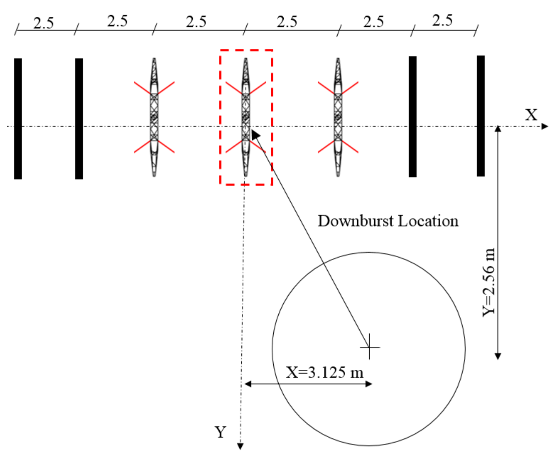


Figure 13: schematic plan view of the test layout

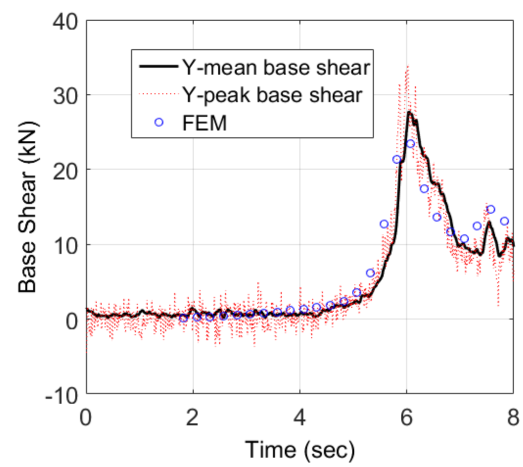


Figure 14: Sample of the test results

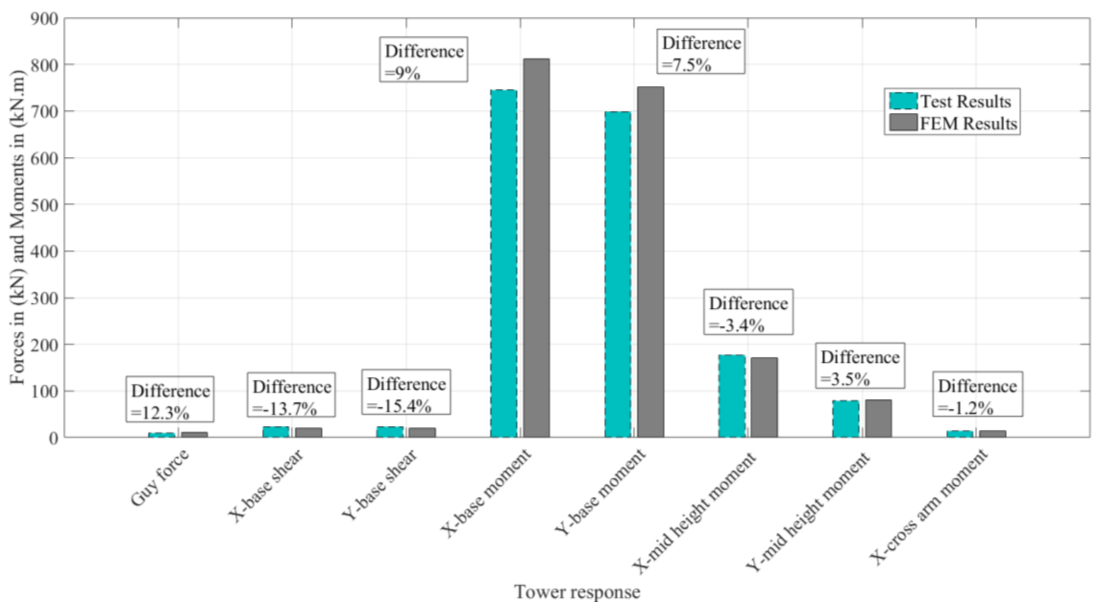


Figure 15: Validation results

5. CONCLUSION

An aeroelastic model is designed and constructed at the University of Western Ontario to test a multi spanned transmission line at WindEEE dome under the downburst loads. The line consists of three towers and other four rigid frames to simulate a total number of six spans. The desired geometric scale is selected to be 1:50. A detailed description of the aeroelastic model design procedures and assumptions is given in this paper. A detailed description of the instrumentations and the boundary conditions is provided. The natural frequencies of the tested towers show a good agreement with those of the prototype tower. The test measurements are compared with findings from the finite element tools that were previously used. A good agreement between the test and FEM is found. The difference is minimal for the base and mid-height moments (~ 9%), while is slightly higher for base shear and guy tension (i.e. ~15%). In general, that validates the findings obtained from our FEM. Results obtained from this test will be very useful to understand the behavior of the lines under downburst wind.

REFERENCES

Aboshosha, H. and El Damatty, A.A., 2014. Effective Numerical Technique to Analyse Transmission Line Conductors under High Intensity Winds. Wind and Structures, Vol. 18, No. 3

Aboshosha H, Bitsuamlak G, El Damatty A. 2015. Turbulence characterization of downbursts using LES. J Wind Eng Ind Aerodyn; 136:44–61.

Aboshosha, H., and El Damatty, A.A. 2015. Engineering method for estimating the reactions of transmission line conductors under downburst winds. Engineering Structures 99, 272-284.

Choi, E.C.C., Hidayat, F.A. 2002. Dynamic response of structures to thunderstorm winds. Prog. Struct. Eng. Mech. 4, 408–416.

CIGRÉ (Conseil International des Grands Réseaux Électriques/ International Council on Large Electrical Systems) (2009). "Overhead line design guidelines for mitigation of severe wind storm damage." Scientific Committee B2 on Overhead Lines, B2. 06.09.

Darwish, M.M. and El Damatty, A.A. 2011. Behavior of self supported transmission line towers under stationary downburst loading. Wind and Structures 14(5), 481-4.

El Damatty, A.A., and Elawady, A. 2015. Critical load cases for lattice transmission line structures under downbursts. 14th International Conference on Wind Engineering, June 21-26, 2015, Porto Alegre, Brazil.

Fujita, T.T. 1985. The downburst: microburst and macroburst. SMRP Research Paper 210, University of Chicago, USA.

"Failure of towers 610 and 611, circuit X503E – 500 kV guyed towers near the Township of Waubaushene, Ontario, August 2, 2006", Failure Investigation Report, HYDRO ONE NETWORKS INC. - Line Engineering, 2006.

Hangan, H., Roberts, D., Xu, Z., Kim, J. 2003. Downburst simulation, Experimental and numerical challenges. Proceedings of the 11th International Conference on Wind Engineering, Lubbock, Texas, Electronic Version.

Holmes, J., Hangan, H., Schroeder, J., Letchford, C., Orwig, K., 2008. A forensic study of the Lubbock-Reese downdraft of 2002. Wind Struct. 11 (2), 137–152

Isyumov, N. 1972. Wind Tunnel Methods for Evaluating Wind Effects on Buildings and Structures, International Symposium on Experimental Mecahnics, June 12-16, The University of Waterloo, Waterloo.

Kim, J. and Hangan, H. 2007. Numerical simulations of impinging jets with application to downbursts. Journal of Wind Engineering and Industrial Aerodynamics 95(4), 279-298.

Kong, L. Jeong, U.Y., and King, J.P.C. 2009. The Hoover Dam bypass project, section model and analysis of equivalent static loads. The University of Western Ontario, Faculty of Engineering, Research Report, Boundary Layer Wind Tunnel Laboratory (BLWTL) SS15.

Loredo-Souza, A., and Davenport, A. G. 2001. A novel approach for wind tunnel modelling of transmission lines. J.Wind Eng.Ind.Aerodyn., 89(11-12), 1017-1029.

McCarthy, P., Melsness, M. 1996. Severe weather elements associated with September 5, 1996 hydro tower failures near Grosse.

Shehata, A.Y., El Damatty, A.A. and Savory, E. 2005. Finite element modeling of transmission line under downburst wind loading. Finite Elements in Analysis and Design, 42(1) 71-89.

Shehata, A. Y., and El Damatty, A. A. 2007. Behaviour of guyed transmission line structures under downburst wind loading. Wind and Structures, an International Journal, 10(3), 249-268.

Zhang Y. 2006. Status quo of wind hazard prevention for transmission lines and counter measures, East China Electric Power, 34(3), 28-31.