The 2018 Structures Congress (Structures18)
Songdo Convensia, Incheon, Korea, August 27 - 31, 2018

Failure analysis of a transmission tower induced by wind loads

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ABSTRACT

An uncertainty analysis method for tower structures subjected to a wind load is presented. Random samples of material properties and section dimensions are generated based on the LHS technique and then used to establish uncertain FEMs for transmission towers. Based on tower models incorporating uncertainty, our analysis reveals that there are six possible initial failure tower members but only one for the deterministic model. Finally, the influence of wind attack angle is discussed.

1. INTRODUCTION

Transmission lines carry electricity and act as the intermediate link for transporting and distributing electric power. The basis of grid interconnection is transmission lines spanning geographical regions. The modern large power grid offers many advantages; however, the probability of local failures leading to large-area power outages is increasing. During a typhoon or hurricane, the failure of transmission lines can lead to paralysis of the power grid, directly affecting subsequent construction, living quality and disaster assistance and potentially causing severe secondary disasters. Historically, numerous transmission lines have collapsed during severe gales and thunderstorms. Thus, it is imperative to study the strength capacity of transmission towers under strong winds and characterize the failure modes to ensure safe operation of the power grid.

High intensity winds (HIWs), associated with tornadoes or microbursts, have attracted much attention due to their strength and association with multiple tower failure accidents. Savory et al. (Savory et al, 2001) performed a dynamic analysis of a lattice tower for two HIW events; the results indicated that tornado-induced failures correlate well with the cumulative evidence in this disaster context, whereas the influence of microbursts is less severe in the configuration modeled in that study. Shehata et al.

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(Shehata et al, 2005) presented a procedure to model and predict the behavior of a transmission line structure subjected to downburst wind loads. For tornado events, the main issue is to determine the most unfavorable locations, which can be defined by the angle of attack and the relative distance between the tornado and structure. Hamada and El Damatty (Hamada and El Damatty, 2011) performed large parametric analyses by varying those two geometric parameters to identify critical tornado locations. Accordingly, Hamada and El Damatty (Hamada and El Damatty, 2015) studied the strength capacity of two guyed transmission lines and concluded that the two selected towers could not withstand the maximum velocity of an F2 tornado.

The dynamic or collapse responses for transmission towers under strong wind are unique due to the deterministic nature of tower models. In other words, the deterministic analysis can only obtain one failure mode, and many other potential failure modes are omitted. To fill such a gap, it is crucial to introduce an uncertainty analysis method into the analysis of transmission tower stability to identify all possible failure paths and estimate the strength capacity accurately.

2. THE PROPOSED UNCERTAINTY ANALYSIS PROCESS FOR TRANSMISSION TOWERS SUBJECTED TO WIND LOADING

The deterministic finite element model (FEM) cannot be used to conduct an uncertainty analysis; thus, the uncertain FEMs should be established based on the generated random samples. An uncertainty analysis process is proposed as exhibited in Fig. 1 (Fu and Li, 2018). The process includes three main steps (Yu et al, 2016), namely, development of the uncertain FEM, identification of collapse status, and determination of the statistics of the acquired capacities and the initial failure members.

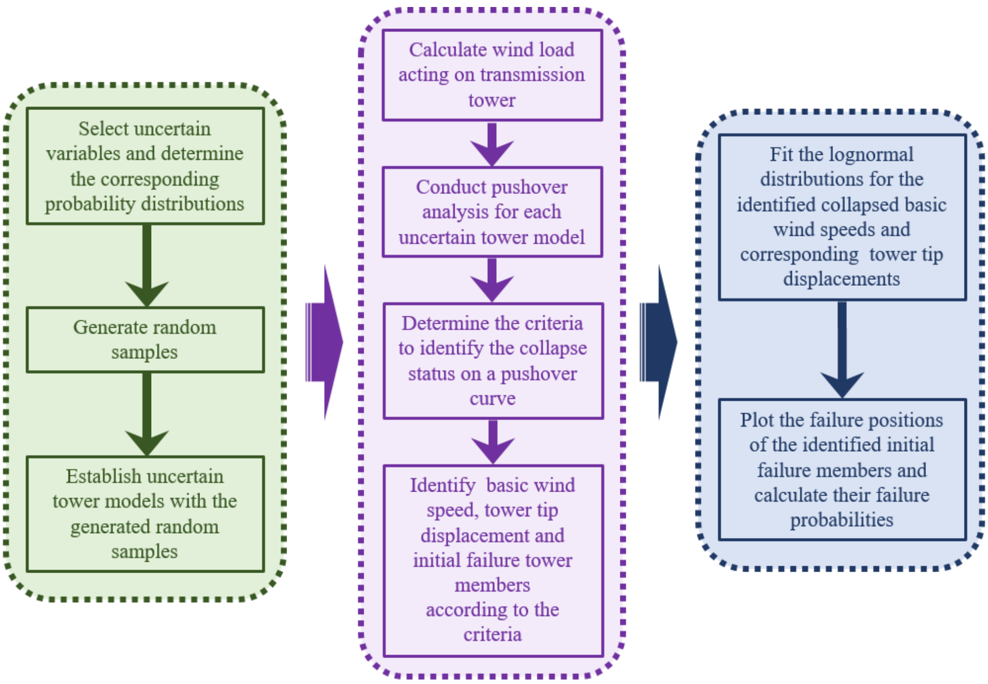

Fig. 1 Process of uncertainty analysis for a transmission tower subjected to a wind load

3. RANDOM VARIABLES

3.1 Material properties

Most towers are made of steel, and the main properties for steel are the density, elastic modulus, Poisson ratio and yield strength. In the reliability design code, the 0.05 fractile of the probability distribution for material strength is used to determine the standard value, whereas the physical properties, such as the elastic modulus and Poisson ratio, can take the 0.5 fractile of the probability distribution, indicating that the standard and average values are equal.

If the material strength conforms to the normal distribution, the standard value yields

$$f_k = \mu_f - 1.645\sigma_f \tag{1}$$

where μ_f and σ_f are the average value and standard deviation of material strength, respectively.

If the material strength conforms to the lognormal distribution, the standard value can be written as

$$f_k = \mu_f \exp\left(-1.645\delta_f\right) \tag{2}$$

where δ_f is the coefficient of variation (COV).

Table 1 Probability distributions of the random material variables

Uncertainty source	Random variable	μ_f	σ_f	Distribution type
Elastic modulus	E_s	206,000 MPa	0.03	Lognormal
Poisson ratio	ν	0.3	0.03	Lognormal
Density	ρ	7800 kg/m3	—	Deterministic
Yield strength for Q235	f_{y_Q235}	263.7 MPa	0.07	Lognormal
Yield strength for Q345	f_{y_Q345}	387.1 MPa	0.07	Lognormal
Yield strength for Q420	f_{y_Q420}	471.3 MPa	0.07	Lognormal

During the structural design or dynamic analysis, the standard values are typically adopted to set the material properties or dimensional parameters. The standard values of the yield strength for steel Q235, Q345 and Q420 are 235 MPa, 345 MPa and 420 MPa, respectively. With the given standard values and coefficients of variance, the average values can be easily obtained based on Eqs. (1)-(2). Table 1 lists the probability distributions of the random material variables that were considered. The random samples are then generated based on the technique of Latin Hypercube Sampling (LHS).

3.2 Section dimensions

The analytical results for angle steel are given in Table 2 and are used in generating random samples for section dimensions.

Table 2 Statistical values of angle steel

Statistical parameter / Section dimension	Average value / Standard value	δ_f	Distribution type
Web thickness	0.985	0.032	Normal
Width	1.001	0.008	Normal

Once the section dimensions are determined, the samples can be generated based on the technique of LHS, similar to the random material variables.

4. UNCERTAIN FEMS FOR TRANSMISSION TOWERS

A 500 kV transmission tower is employed to perform the uncertainty analysis. The cross-sections of tower members consist of angle steel. The height of the tower is 99.9 m, and the material is taken as Q235-, Q345- and Q420-type steel. The Bilinear Isotropic Hardening Plasticity model is used to simulate the constitutive model of the steel material (Fu et al, 2016). The elastic modulus of Q235-, Q345- and Q420-type steel is uniformly 206 GPa, and the yield strength is 235 MPa, 345 MPa and 420 MPa, respectively. The 4-bundled conductors and ground wire consist of LGJ630/45 and JLB20A-150, respectively. The straight-line distance between two towers is 500 m, and the length of insulator string is 6.654 m with a mass of 285.6 kg.

The ANSYS software is used to build the FEM of the transmission tower-line system. A further simplified FEM ignoring the transmission line is established as demonstrated in Fig. 2, and all masses and loads of the transmission line are applied to the suspension point of the cross arm. Based on the generated random samples in Section 3, the 100 FEMs incorporating uncertainty are established.

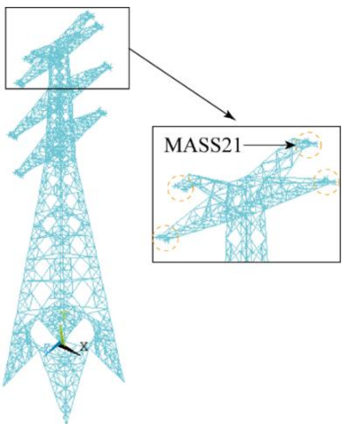

Fig. 2 Simplified model

5. RESULTS

Assuming that the wind direction is perpendicular to the direction along the transmission line, the wind loads with various basic wind speed levels are calculated and range from 11 to 50 m/s. The static non-linear responses for each uncertain tower model subjected to wind loads, with a gradually increasing basic wind speed until the tower collapses, are then calculated. The observation point for the tower tip displacement during the uncertainty analysis is shown in Fig. 3.

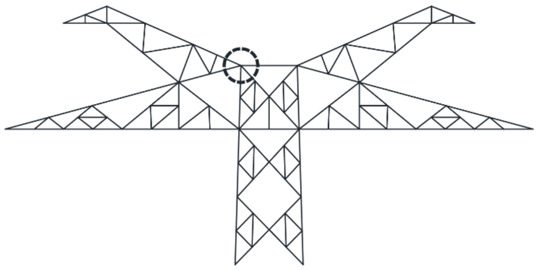

Fig. 3 Observation point of tower tip displacement

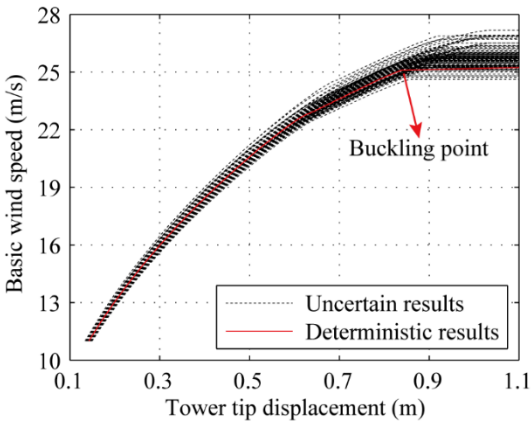

Fig. 4 The pushover curves for both uncertain and deterministic tower models

Along with the uncertainty analysis, the frequently used deterministic FEM is also implemented, with the standard values of material properties and section dimensions. The pushover curves for both uncertain and deterministic tower models are illustrated in Fig. 4, which shows that each curve has its own buckling point. It is assumed that the tower will collapse once the displacement reaches or exceeds the buckling point (Fu et al, 2016); the wind speed corresponding to the buckling point is defined as the collapse basic wind speed.

As shown in Fig. 4, the red curve is located in the middle of the uncertain pushover curves, and the collapse basic wind speed is smaller than most of the results that incorporate uncertainty. The main reason is that most material properties and section dimensions for the deterministic tower model take the 0.5 fractile of the probability distribution, whereas the deterministic material strength adopts the 0.05 fractile of the probability distribution. Consequently, the strength capacity of the deterministic tower model is weaker; its stiffness lies at approximately the median value among the 100 uncertain tower models.

The collapse basic wind speeds and displacements for each curve can be extracted from Fig. 4, and then the cumulative distribution curves, fitted with the lognormal distribution, can be plotted as shown in Fig. 5 and Fig. 6. The 95% confidence bounds are calculated as the dotted lines plotted in both Fig. 5 and Fig. 6. Most of the raw data lie in the confidence bounds, indicating that the raw data are consistent with the lognormal distribution.

The collapse basic wind speed and tower tip displacement for the deterministic tower model are 25.09 m/s and 0.838 m, respectively, corresponding to the probability of 11.50% and 10.78% in Fig. 5 and Fig. 6. The deterministic tower model is found to underestimate the strength capacity for most conditions. In fragility analysis, the intensity measure corresponding to the probability of 10% is typically regarded as the critical value that determines whether the structure is predicted to collapse. The basic wind speed and tower tip displacement corresponding to 10% of the cumulative distribution curves are 25.05 m/s and 0.836 m, respectively, and the corresponding relative errors between the deterministic and uncertainty analysis results are only 0.16% and 0.24%, indicating that the standard values of the deterministic tower model are determined reasonably when designing the transmission tower.

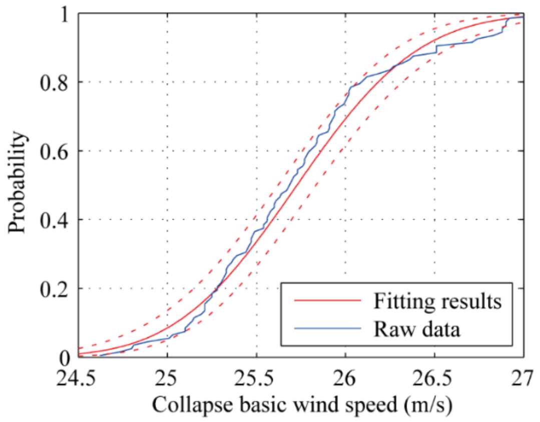

Fig. 5 Cumulative distribution curves of the collapse basic wind speed

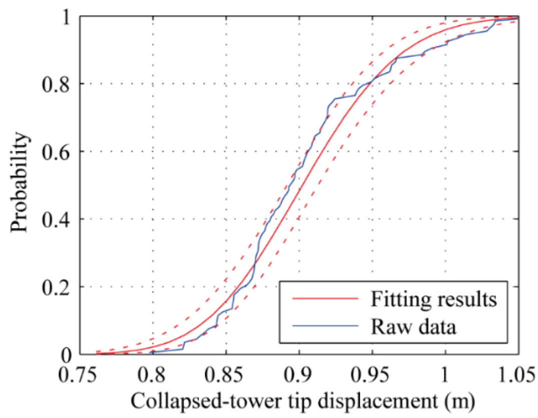

Fig. 6 Cumulative distribution curves of the collapsed-tower tip displacement

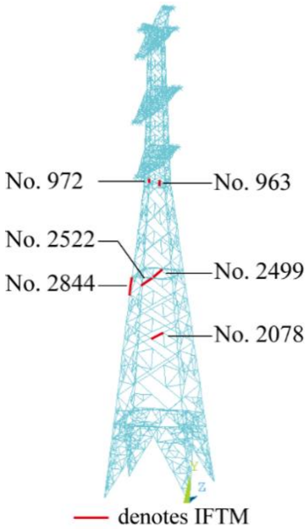

Fig. 7 Initial failure positions of the tower members

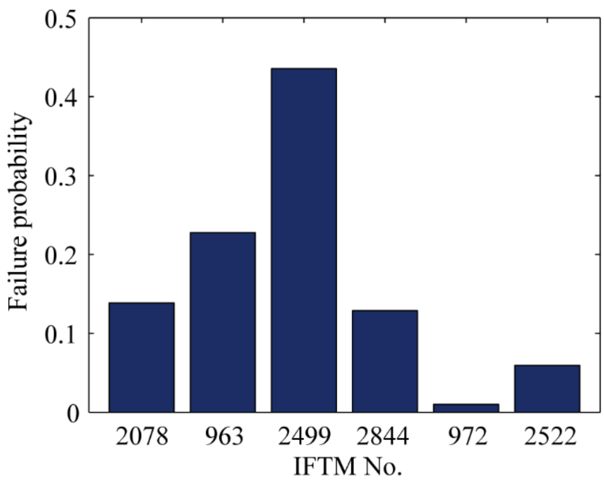

Fig. 8 The failure probabilities of the IFTMs

For the deterministic tower model, the number of initial failure tower member (IFTM) is 2499. Due to uncertainties in the material properties and section dimensions, the IFTMs and failure path differ from the deterministic analysis results. When conducting the static non-linear analysis for the 100 uncertain tower models, the IFTMs are identified and captured simultaneously. Eliminating repeat numbers, the numbers of IFTMs are 2078, 963, 2499, 2844, 972 and 2522. Fig. 7 provides the six initial failure positions of tower members, indicating two IFTMs are located near the connection between the cage and tower body, and the rest are located in the middle of the tower body. The failure probabilities for each IFTM are calculated as provided in Fig. 8. IFTM no. 2499 has the largest failure probability of 43.56%, which coincides with the deterministic analysis result. The failure path is more complex when considering the uncertainty of material properties and section dimensions, and it is necessary to perform an uncertainty analysis for the transmission towers to identify all potential failure modes and analyze their failure probabilities.

5.1 Influence of the wind attack angle

Although the uncertainty analysis has been performed with the consideration of uncertain material properties and section dimensions, the influence of wind attack angle, also an important uncertain variable, has not yet been discussed. For a real tower structure, the wind may come from any direction; thus, the wind attack angle can be expected to change with the wind direction. Different wind attack angles can lead to different load distributions in two horizontal directions that will result in different responses (Deng et al, 2016; Yang et al, 2016). Due to the variation in a natural environment, it is essential to study the influence of the wind attack angle on the cumulative distribution curve and IFTM for the transmission tower.

The tower-line system exhibits biaxial symmetry in both X- and Y-directions, and the wind attack angle is defined in Fig. 9. The Chinese standard considers that the most unfavorable wind attack angles are 0°, 45°, 60°or 90°.

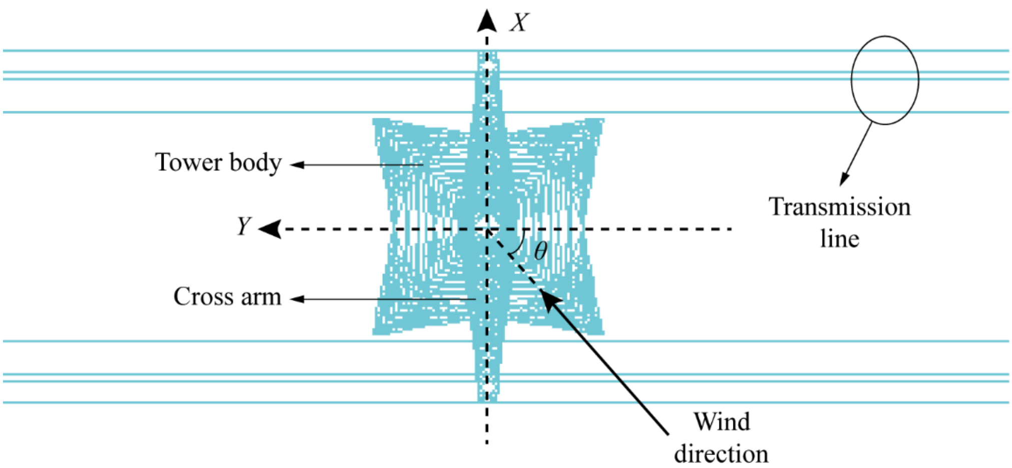

Fig. 9 The definition of wind attack angle for a tower-line system

By applying the uncertain tower model to perform the static non-linear analysis with various wind attack angles, the collapse basic wind speeds and IFTMs are identified, and the cumulative distribution curves and failure positions are obtained as demonstrated in Fig. 10 and Fig. 11, respectively. Fig. 10 indicates that the cumulative distribution curves move left with increasing wind attack angle and that the most unfavorable wind attack angle is 0°.

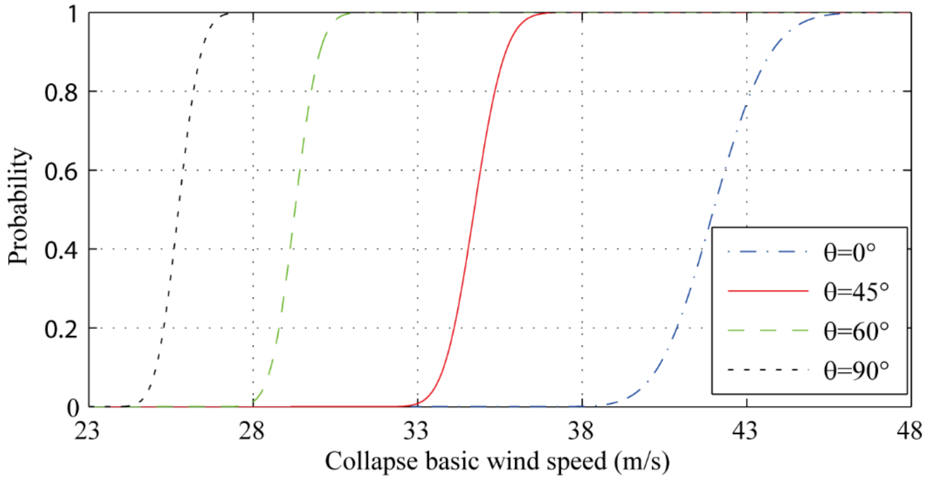

Fig. 10 Cumulative distribution curves of the collapse basic wind speed for various wind attack angles

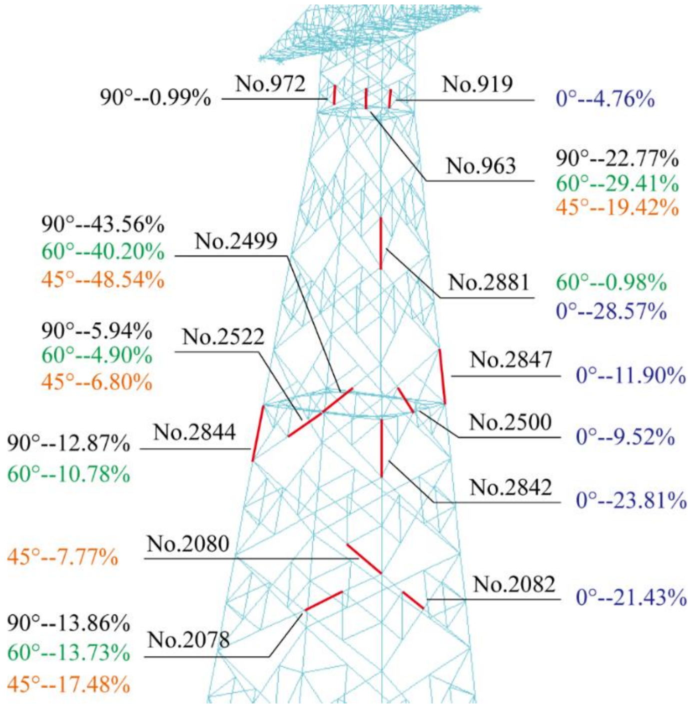

Fig. 11 Initial failure positions and corresponding probabilities for various wind attack angles

Fig. 11 labels the failure positions and corresponding probabilities in the tower sketch for various wind attack angles, where the red lines denote the initial failure members and θ--P means that the failure probability is P at a wind attack angle of θ. More than half of the IFTMs lie in the middle of tower body, and three initial failure members are located near the connection between the cage and tower body, indicating that the most possible failure position occurs at the middle of the tower body for this transmission tower.

6. SUMMARY AND CONCLUSIONS

In this study, an uncertainty analysis method for the transmission tower under a wind load is presented that can be used to estimate the strength capacity and predict the failure path. A 500 kV transmission tower is employed to perform the uncertainty analysis, and significant conclusions drawn from the numerical simulation are summarized below:

(1) The uncertainty of material properties has a stronger influence than the uncertainty of section dimensions.
(2) The wind attack angle has a strong influence on the strength capacity and cumulative distribution curve; the most unfavorable wind attack angle is 0° for the employed tower.
(3) The failure position of highest likelihood for the employed tower is the middle of the tower body.

ACKNOWLEDGMENTS

This research was supported by the National Natural Science Foundation of China (grant nos. 51708089, 51421064), China Postdoctoral Science Foundation (grant no. 2017M620101) and the Fundamental Research Funds for the Central Universities (grant no. DUT17RC(3)007).

REFERENCES

Deng, H.Z., Xu, H.J., Duan, C.Y., Jin, X.H., Wang, Z.H. (2016), "Experimental and numerical study on the responses of a transmission tower to skew incident winds", *J. Wind. Eng. Ind. Aerod.*, **157**, 171-188.

Fu, X., Li, H.-N. (2018), "Uncertainty analysis of the strength capacity and failure path for a transmission tower under a wind load", *J. Wind. Eng. Ind. Aerod.*, **173**, 147-155.

Fu, X., Li, H.-N., Li, G. (2016), "Fragility analysis and estimation of collapse status for transmission tower subjected to wind and rain loads", *Struct. Saf.*, **58**, 1-10.

Hamada, A., El Damatty, A. (2011), "Behaviour of guyed transmission line structures under tornado wind loading", *Comput. & Struct.*, **89** (11), 986-1003.

Hamada, A., El Damatty, A. (2015), "Failure analysis of guyed transmission lines during F2 tornado event", *Eng. Struct.*, **85**, 11-25.

Savory, E., Parke, G.A., Zeinoddini, M., Toy, N., Disney, P. (2001), "Modelling of tornado and microburst-induced wind loading and failure of a lattice transmission tower", *Eng. Struct.*, **23** (4), 365-375.

Shehata, A., El Damatty, A., Savory, E. (2005), "Finite element modeling of ransmission line under downburst wind loading", *Finite Elem. Anal. Des.*, **42** (1), 71-89.

Yang, F., Dang, H., Niu, H., Zhang, H., Zhu, B. (2016), "Wind tunnel tests on wind loads acting on an angled steel triangular transmission tower", *J. Wind. Eng. Ind. Aerod.*, **156**, 93-103.

Yu, X., Lu, D., Li, B. (2016), "Estimating uncertainty in limit state capacities for reinforced concrete frame structures through pushover analysis", *Earthq. Struct.*, **10** (1), 141-161.