Capacity of transmission towers in a transmission line under typhoon wind loads

Shucheng Yang [1,2], Shouke Li [3], Sai Gong [1]

[1]Highway College, Chang'an University, Xi'an, China, syang325@chd.edu.cn
[2]Dept. of Civil & Environmental Engineering, Western University, London, Canada, syang325@uwo.ca
[3]School of Civil Engineering, Hunan University of Science and Technology, Xiangtan, China, lishouke@hnust.edu.cn

SUMMARY:

Design of the transmission towers is critical considering that the damage of independent tower due to severe wind event may cause the failure of the entire tower-line system. Assessment of capacity curves of four types of transmission towers in a transmission line is carried out using numerical models validated by field measurement and simulated non-stationary spatially varying typhoon wind loads. A field measurement is conducted and the measured responses and dynamic characteristics of the transmission tower under typhoon wind loads are used to validate the numerical model. By conditionally simulating the non-stationary spatially varying typhoon wind fields, the responses of the tower under typhoon wind loads are calculated. A modelling error defined by the ratio of measured to the calculated responses is also investigated. For the assessment of the capacity of transmission towers, the incremental dynamic analysis and the nonlinear static pushover analysis are employed. The obtained capacities of four types of transmission towers from a transmission line are statistically investigated considering the effect of record-to-record variability of wind, the effect of material uncertainty, as well as the effect of wind direction.

Keywords: transmission tower, non-stationary typhoon wind fields, capacity curve

1. INSTRUCTION

Unlike common structures that are located at single sites, the transmission tower-line spatially distributed in hundreds of kilometres and are vulnerable to wind hazards, especially at the open coastal terrain in cyclonic region. Design of the towers within a transmission line is therefore critical since independent failure of the tower would generally cause the failure for the overall tower-line system. For example, damage of the transmission tower due to typhoon wind loads has been reported by Tomokiyo et al. (2004), indicating that failure of the tower-line system is due to the changes in tensile forces of the towers that had already collapsed. For such a case, the design is relying on the capacity of transmission towers considering the interaction between tower and wires under wind loadings. To estimate the ultimate response of a transmission tower under wind loads, a numerical model with the capability of representing the nonlinear behaviour of the structure is often adopted. The nonlinear static pushover analysis (NSPA) has been performed by Mara and Hong (2013) numerically. On the other hand, the nonlinear inelastic dynamic analysis (e.g., incremental dynamic analysis(IDA)) that is needed to estimate the peak responses or capacity curve of the tower subject to the spatial-temporally varying wind was performed by Yang et al. (2017). In addition, considering that the transmission tower-line system spreads over thousands of kilometres, the towers facing different directions withstand varying wind loads due to their exposure areas of the steel lattice tower and the wires.

However, the validation for the accuracy of the predicted dynamic responses by using the developed numerical model of the transmission tower under fluctuating wind loads is lacking. Such a validation usually requires a comparison between the tower responses from on-site measurements and from the numerical simulations. Consequently, the objective of this study is two folds: a) the use of full-scale measurements for a self-supported lattice tower during a typhoon event to validate the simplified numerical model for accurately predicting the peak responses considering tower-wire interaction and b) the assessment of the capacity of the tower within a tower-line system using conditionally simulated spatial-temporally varying typhoon wind loads.

2. DESCRIPTION OF THE TRANSMISSION LINE AND MODELLING

2.1. Design of the Transmission Towers and Finite Element Modelling

The transmission towers designed with the same tower head (i.e., lattice panels above the cross-arm of the tower) but different lower panels are shown in Fig. 1. The transmission towers with four designs are modelled independently by adopting the material properties and geometric variables of the tower, wire, and insulator. The material and geometric nonlinearities are considered. An end-spring is developed for connecting the tower to remote towers. The finite element models are also illustrated in Fig. 1.

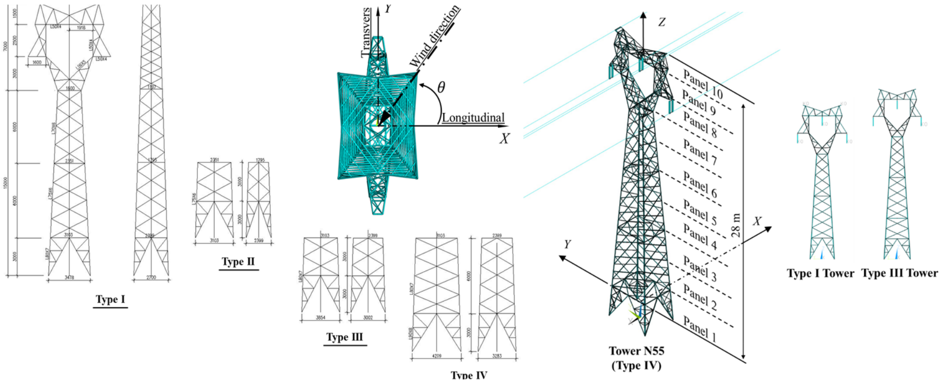


Figure 1. Design of the towers, definition of the wind direction, and illustration of the finite element model

2.2. Simulation of Non-stationary Typhoon Wind Field

The wind fluctuations exhibit non-stationary features such as the time-varying mean wind speed and the amplitude modulation in a typhoon-induced wind field. The simulation of non-stationary spatially varying wind speeds acting on the towers can be carried out using the spectral representation method (SRM) (Shinozuka and Jan, 1972) for power spectral density function (Boore, 2009) and coherency functions (Hong and Liu, 2014). Following Hong and Hong (2021), the nonhomogeneous nonstationary random field is formulated in the space and transformed time domain (i.e., the space and τ domain), which becomes homogeneous stationary field. Once the representation of the random field in the transformed domain is obtained, it is mapped back to the original space and time domain. In such a way, the observed spectra from field measurement during a typhoon event can be used to simulate the spatial-temporally varying typhoon wind field.

3. VALIDATION OF THE FINITE ELEMENT MODEL USING FIELD MEASUREMENT

A transmission tower in the selected transmission line was instrumented for the field measurement, which is located 45 km away from the south-west direction of the landfall site of a typhoon event. Fig. 2 shows the obtained typical wind characteristics measured from the instrumented tower.

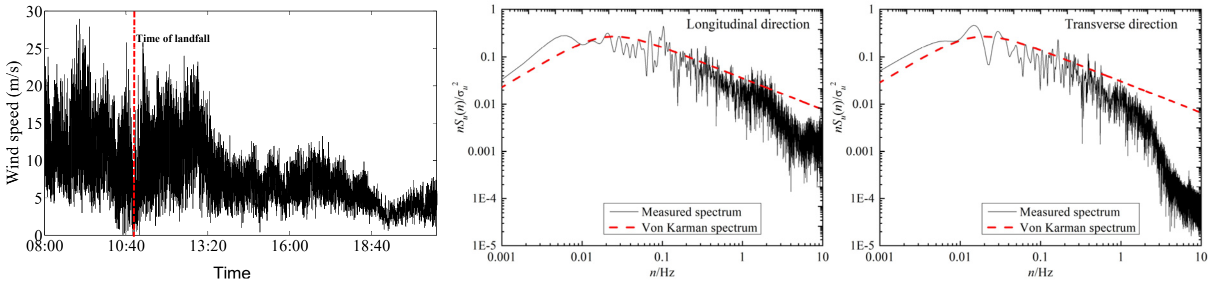


Figure 2. Typical wind characteristics recorded from the instrumented tower.

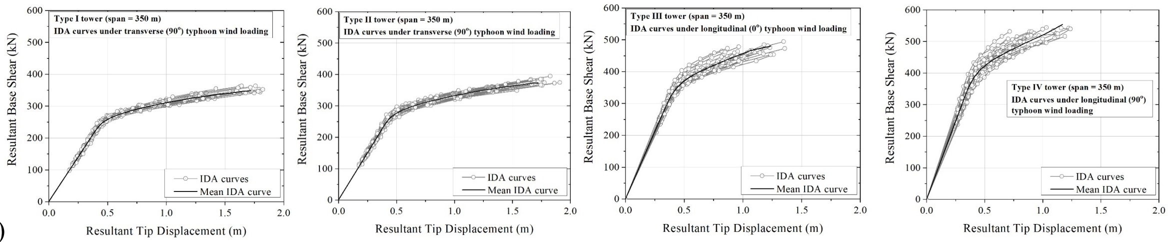
The statistics of the ratio of measured to calculated responses, $r_{m/c}$, are given in Table 1. Considering that the peak response of the tower during a scenario event is often adopted as the damage measure for representing the capacities (Mara and Hong, 2013; Yang et al., 2017), and that the less-than-unity $r_{m/c}$ would lead to a conservatively estimated capacity of the tower, the FE modelling is acceptable for evaluating the capacity of a tower in the transmission line.

Table 1. Statistics of the ratio of measured to calculated responses.

Quantity	Measurement 1		Measurement 2		Measurement 3		Measurement 4	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Peak	0.896	0.114	0.900	0.109	0.911	0.112	0.932	0.107
RMS	0.823	0.127	0.830	0.124	0.841	0.133	0.845	0.135

4. CAPACITY CURVES OF THE TRANSMISSION TOWER

Using 25 sets of spectra from the measured typhoon winds for the conditionally simulated spatial-temporally varying wind speeds, the IDA for each type of the towers in the transmission line is carried out. The obtained IDA capacity curves are shown in Fig.3a which illustrates the effect of record-to-record variability of the winds. Considering that the material uncertainties may impact significantly on the capacity of the towers, the NSPA is also performed with 100 simulations by adopting the material uncertainties of the steel angel members, the wires, and the insulators. The obtained NSPA capacity curves are shown in Fig. 3b. To investigate the effect of wind direction on the capacity, the IDA is conducted considering the uncertainties inherent in the simulated wind speeds and the material properties for the wind directions of 0°, 30°, 45°, 60° and 90°. The obtained statistics of the yield capacity for the type IV tower are given in Table 2.



a)

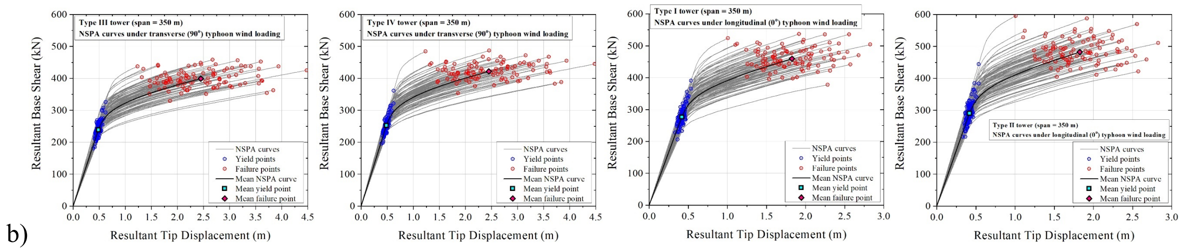


Figure 3. Capacity curves of the transmission towers: a). IDA; b). NSPA.

Table 2. Statistics of the obtained yield capacity of Type IV tower.

Wind Direction	0° (Longitudinal)	30°	45°	60°	90° (Transverse)
Mean (kN)	344.4	268.9	237.3	246.2	252.4
STD (kN)	69.3	53.2	47.7	50.5	55.8
COV	0.194	0.198	0.201	0.205	0.221

5. CONCLUSIONS

Assessment of capacity curves of four types of transmission towers in a transmission line is conducted using numerical models validated by field measurement and simulated non-stationary spatially varying typhoon wind loads. The obtained statistics of the defined modelling error indicate that the calculated responses are generally greater than the measured responses of the tower within an acceptable range, which leads to conservatively estimated capacities of the transmission towers. The obtained capacities from the incremental dynamic analysis indicate that the effect of record-to-record variability is not significant due to the relative low turbulence intensity of typhoon winds, whereas the obtained capacities from the nonlinear static pushover analysis show a greater variability due to the material uncertainties. The effect of wind direction on the tower capacity is also investigated, indicating that the transmission tower is vulnerable in the 45° of wind direction with smallest capacity. It is also indicated that the variability of the capacity is greatest in the wind direction of 90° since the contribution of wind loadings from the wires is most significant for such a case. The obtained statistics of the modelling error and the capacity of the tower can be further probabilistically characterized to provide essential information for the reliability evaluation of the overall transmission line under scenario typhoon events.

REFERENCES

Boore, D.M., 2009. Comparing stochastic point-source and finite-source ground-motion simulations: SMSIM and EXSIM. Bulletin of the Seismological Society of America, 99(6), pp.3202-3216.

Hong, P. and Hong, H.P., 2021. Simulation of Nonstationary and Nonhomogeneous Wind Velocity Field by Using Frequency–Wavenumber Spectrum. Frontiers in Built Environment, 7, p.636815.

Hong, H.P. and Liu, T.J., 2014. Assessment of coherency for bidirectional horizontal ground motions and its application for simulating records at multiple stations. Bulletin of the Seismological Society of America, 104(5), pp.2491-2502.

Mara, T.G. and Hong, H.P., 2013. Effect of wind direction on the response and capacity surface of a transmission tower. Engineering structures, 57, pp.493-501.

Shinozuka, M. and Jan, C.M., 1972. Digital simulation of random processes and its applications. Journal of sound and vibration, 25(1), pp.111-128.

Tomokiyo, E., Maeda, J., Ishida, N. and Imamura, Y., 2004. Typhoon damage analysis of transmission towers in mountainous regions of Kyushu, Japan. *Wind & structures*, *7*(5), pp.345-357.

Yang, S.C., Liu, T.J. and Hong, H.P., 2017. Reliability of tower and tower-line systems under spatiotemporally varying wind or earthquake loads. Journal of Structural Engineering, 143(10), p.04017137.