# Fragility Assessment of Overhead Transmission Towers under Typhoon and Earthquake Multi-Hazard Events

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## 1. Introduction

The Korean peninsula is located on a complex tectonic zone where the Eurasian plate meets the Pacific plate. This susceptibility to earthquakes along with the exposure to massive typhoons pose a multi-hazard risk to Transmission Line Systems (TLSs). Failure of TLSs by these hazards can incur significant social and economic losses. An example is the 2003 widespread power outages due to Typhoon Maemi which left 1.47 million customers in South Korea without power [1]. The vulnerability of TLSs to seismic events was evident in the aftermath of 1999 Chi-Chi earthquake in Taiwan, where 109 transmission towers either collapsed, tilted, or deformed by seismic effects [2]. Although the probability of a concurrent typhoon and earthquake is negligible, scenarios may take place where the two hazards affect a region in a short period of time, such that there is not sufficient time to completely repair damage to TLSs sustained from the first event. Prior studies are conducted on the future performance of other structural systems subjected to multi-occurrence as well as multi-type multi-occurrence events, in terms of life-cycle cost [3, 4]. Furthermore, the compound risk from wind hazards and aging in utility poles were studied through multi-dimensional fragility curves [5]. These fragility functions are the key components of risk and resilience assessment of power distribution systems [6]. However, the accumulation of damage in transmission towers from one event to the other has been neglected in the fragility assessment of TLSs.

To address the aforementioned limitations, the reliability of transmission towers under earthquake-typhoon multi-hazard events is investigated in this study. To this end, a nonlinear high-fidelity Finite Element (FE) model of a double circuit steel lattice transmission tower is developed in OpenSees platform. This FE model captures various complexities in the behavior of TLSs, as well as several sources of material and geometric uncertainties in transmission towers. Time history analyses are conducted for realizations of the tower, where earthquake and typhoon loading are applied sequentially in time domain to realistically simulate the physical phenomena. In these analyses, the intensity of both hazards is incrementally increased, and the collapsed realizations are investigated for element failures. The number of collapsed realizations in every pair of multi-hazard intensities are used as input to the probabilistic machine learning classification method Multiple Logistic Regression (MLR) to develop a multi-hazard fragility surface of transmission towers in earthquake-typhoon multi-hazard events. These fragility models can be used in risk assessment methods in order to enhance the reliability and resilience of the power grid and mitigate the likelihood of loss of offsite power for nuclear power plants.

## 2. Methodology

### *2.1. Finite Element Modeling*

To accurately capture the nonlinear behavior of transmission towers, material nonlinearity, p-delta effects, buckling of lattice elements, joint slippage, and joint failure should be considered. The material behavior of steel elements is considered as uniaxial bilinear with kinematic hardening to account for the post-yielding effects and material nonlinearity of the elements.

Buckling, the instability under compressive forces due to imperfection, is a common phenomenon in steel elements of transmission towers, which can noticeably affect the behavior of steel elements as well as the structural responses of the system of transmission towers. In a recent study, Darestani et al. [7] concluded that each lattice element should be divided into four members in order to accurately capture buckling in OpenSees. Furthermore, a camber displacement equal to 0.05 to 0.1% of the undeformed length of an element should be applied to the middle node.

Bolted connections are the most common type of connections between steel elements in transmission towers. From construction perspective, it is preferred to have larger holes than the diameter of the bolts to help with assembling elements. The consequent gap between the edge of the holes and the bolts causes the joint slippage phenomenon. This behavior, which may lead to increase in the lateral displacements of transmission towers and decrease in the load bearing capacity, is precisely represented by the joint slippage model developed by Darestani et al. [7]. Using this model, the backbone behavior of one connection type is illustrated in Fig. 1.

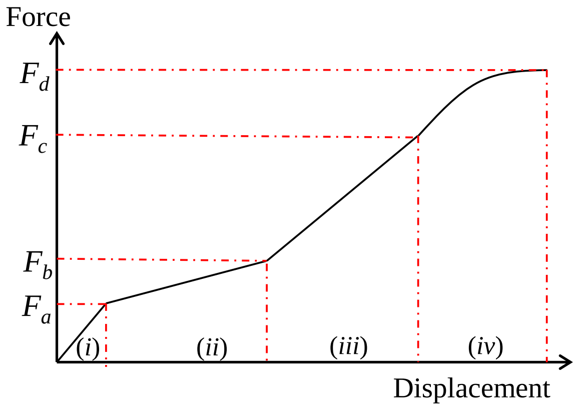


Fig. 1. Backbone curve of joint slippage model

### *2.2. Hazard models*

To simulate the impact of earthquake, a ground motion suite consisting of 22 far-field ground motions in two directions, provided by FEMA-P695 is selected [8]. Thus, 44 ground motions are used in this study. To account for the record-to-record variability and avoid intra-event correlations, at most two records are selected from a single seismic event.

For the typhoon loading on transmission towers, the static equivalent gust wind load model in ASCE07 for non-building structures is adopted here [9]. According to this model, the wind force per unit length can be calculated as,

$$f_w = q_z G C_f D \tag{1}$$

where $q_z$ is the velocity pressure at height $z$ of the tower, $G$ is the gust-effect factor, $C_f$ is the force coefficient, and $D$ is the diameter of the element in plane perpendicular to the wind direction. $q_z$ is estimated using,

$$q_z = 0.5\rho K_z K_d K_{zt} K_e V^2 \tag{2}$$

where $\rho$ is the air density, $K_z$ is the velocity pressure exposure coefficient, $K_d$ is the wind directionality factor, $K_{zt}$ is the wind topographic factor, $K_e$ is the elevation factor, and $V$ is the wind speed.

### *2.3. Fragility analysis method*

In order to have a reliable assessment of the performance of transmission towers, uncertainties should be considered. Several sources of uncertainty are accounted for in this study, such as material properties, geometry, imperfection, eccentricity, and loading.

As this study is interested in the probability of collapse of transmission towers, the outcomes of FE analyses are classified into two groups of collapsed (class 1) and survived (class 0). A Multiple Logistic Regression (MLR) model is applied to the results to determine the probability of belonging to each class of data. This probability for the collapse class yield the collapse fragility of the tower. The MLR model has the following form.

$$p(X) = e^{\beta_0+\beta_1X_1+\beta_2X_2} \Big/ 1 + e^{\beta_0+\beta_1X_1+\beta_2X_2} \tag{3}$$

where $\beta_0$, $\beta_1$, and $\beta_2$ denote the regression coefficients of the MLR model. For the case of this study, $X_1$ and $X_2$ are the intensity measures of typhoon and earthquake hazards, i.e. wind speed and peak ground acceleration (PGA), respectively. To select the form of the basis function of the MLR model, a stepwise logistic regression process is applied and the linear form without interaction is selected as it results in minimum Akaike Information Criterion (AIC) value.

## 3. Numerical study

The studied transmission tower in this project is a double circuit steel lattice transmission tower with dimensions illustrated in Fig. 2. The span length of this transmission tower is 258 meters. The transmission tower carries six lines of conductors and it is assumed that impact of structural couplings is negligible due to multiple spans with similar properties. Consequently, a separate transmission tower is modeled individually. In this study to demonstrate the reliability of transmission tower, typhoon and earthquake loading is considered in the transverse direction. Therefore, the wind load on the conductors are considered.

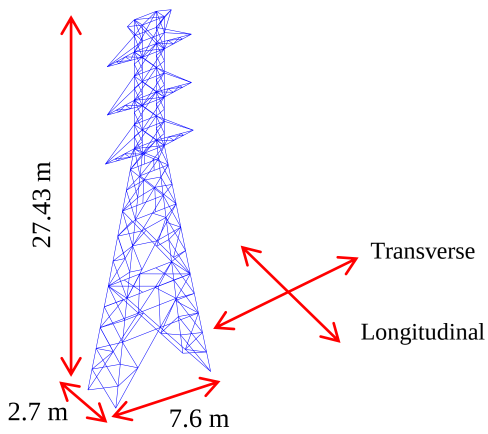


Fig. 2. Schematic of studied transmission tower

44 realizations of the tower are generated by using Latin Hypercube Sampling (LHS) method and each realization is randomly assigned to one ground motion. Then in a set of time history analyses with a specified intensity for earthquake and typhoon, the scaled ground motion record is applied to the tower. This is followed by 120 seconds of typhoon loading and unloading sequence. During these time history analyses, responses of elements are recorded and the failure of each element is investigated. Furthermore, when the computational model under excessive loads does not converge, the results are investigated for the formation of a failure

mechanism in the tower which often involves failure of several key elements.

## 5. Fragility Assessment

A grid of typhoon and earthquake intensity measures is created as shown in Fig. 4 to cover a wide range of multi-hazard scenarios. A set of time history analyses for each intensity pair in the grid is performed and the number of collapsed samples are determined, which are shown in Fig. 4. As expected, the increase in the number of collapses is correlated with both intensity measures. The effect of typhoon loading after prior earthquake can be observed for wind speeds larger than 100 mph, where the increase is more considerable.

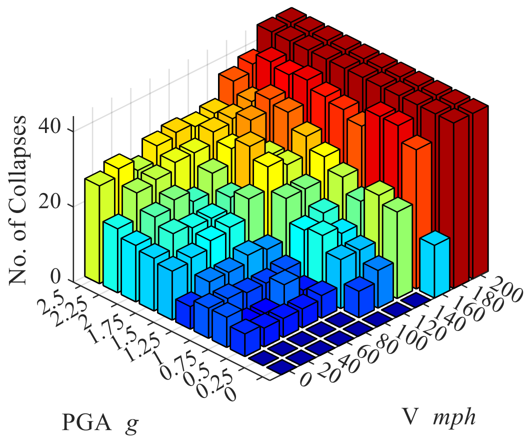


Fig. 4. Number of collapsed samples in earthquake-typhoon multi-hazard event

Using the MLR model explained in section 2.3, the probability of failure of the transmission tower is estimated using the obtained collapse data. The derived fragility surface is illustrated in Fig. 5. It is worth mentioning that collapses in Fig. 4 account for any collapse regardless of occurrence in earthquake or typhoon. Therefore, the probabilities in Fig. 5 represent the probability of failure in either prior earthquake or following typhoon.

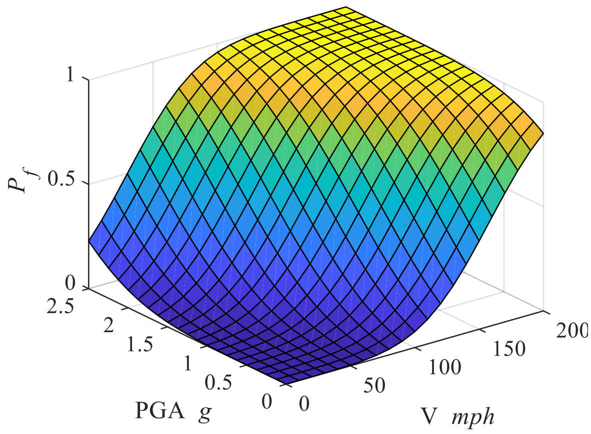


Fig. 5. Fragility surface in earthquake-typhoon event using MLR

Decomposing this fragility surface using total probability theorem, the probability of collapse in typhoon after surviving the prior earthquake event can be derived as,

$$P(C_T|S_E, IM_T, IM_E) = \frac{P(C_T|IM_T, IM_E) - P(C_T|IM_E)}{P(S_E|IM_E)} \quad (1)$$

where $C$ and $S$ represent the event of collapse and survival, respectively. Subscript $E$ and $T$ stand for earthquake and typhoon, and $IM$ is the intensity measure of each hazard. This procedure is implemented for the probabilities in Fig. 5 and the resulting fragility surface is illustrated in Fig. 6, which represents the probability of collapse in typhoon after experiencing and surviving the prior earthquake.

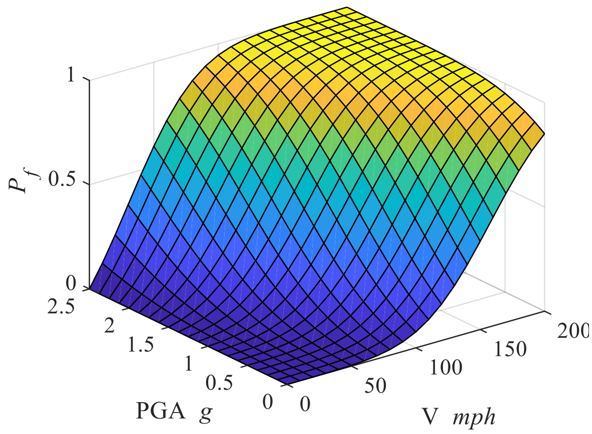


Fig. 6. Fragility surface for failure in typhoon in earthquake-typhoon event using MLR

The typhoon fragility curves for developed fragility surfaces are illustrated in Fig. 7, with respect to the intensity of the prior earthquake event. In this figure, dashed lines represent the probability of failure in either earthquake or typhoon and solid lines illustrate typhoon fragility curves after surviving the prior typhoon. As can be observed in smaller earthquake intensities, the difference between fragility curves is negligible, implying that failures are mostly due to typhoon loading.

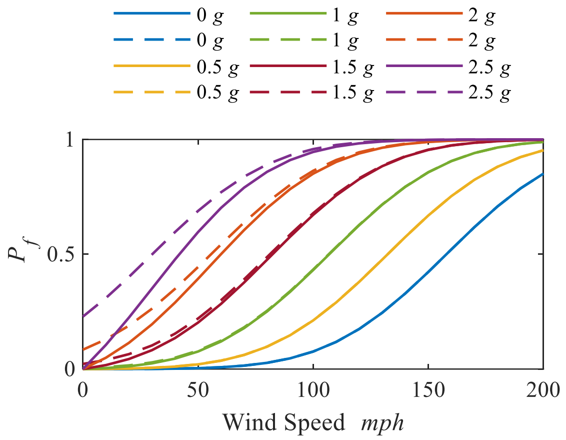


Fig. 7. Fragility curve in earthquake-typhoon event using MLR (solid and dashed lines present $P(C_T|S_E, IM_E, IM_T)$ and $P(C_T|IM_E, IM_T)$, respectively)

### 6. Summary and conclusions

Multi-hazard fragility of transmission towers for earthquake-typhoon events is addressed in this study. A nonlinear high-fidelity Finite Element (FE) model of steel lattice transmission towers is developed to capture key complexities in the behavior of towers along with several sources of uncertainty. 44 realizations of the tower are randomly assigned to 44 ground motions, and a set of earthquake-typhoon time history analyses are conducted. The results captured emergence of multiple element failure patterns in the transmission tower.

In the time history analyses, the intensities of both hazards are increased incrementally and based on the state of each realization of the tower, either collapse or survival, the number of collapsed realizations are recorded. The data gathered by this process are used in a Multiple Logistic Regression (MLR) model to probabilistically classify the input data. The outputs of this model are presented in the form of multi-hazard fragility surface of transmission towers. These results will enhance the completeness of risk analyses for critical facilities against low probability-high consequence multi-hazards.

### REFERENCES

[1] Moon, B. W., Park, J. H., Lee, S. K., Kim, J., Kim, T., & Min, K. W. (2009). Performance evaluation of a transmission tower by substructure test. Journal of Constructional Steel Research, 65(1), 1-11.

[2] G. C. Lee and C.-H. Loh, The Chi-Chi, Taiwan, Earthquake of September 21, 1999: Reconnaissance Report. Multidisciplinary Center for Earthquake Engineering Research Buffalo, NY, 2000.

[3] Fereshtehnejad, E., and Shafieezadeh, A. (2016) Multiple hazard incidents lifecycle cost assessment of structural systems considering state-dependent repair times and fragility curves. Earthquake Engng Struct. Dyn., 45: 2327− 2347.

[4] Fereshtehnejad, E., & Shafieezadeh, A. (2018). A multi-type multi-occurrence hazard lifecycle cost analysis framework for infrastructure management decision making. Engineering Structures, 167, 504–517.

[5] Darestani, Y. M., & Shafieezadeh, A. (2019). Multi-dimensional wind fragility functions for wood utility poles. Engineering Structures, 183, 937–948.

[6] Dehghani, N. L., Darestani, Y. M., & Shafieezadeh, A. (2020). Optimal Life-Cycle Resilience Enhancement of Aging Power Distribution Systems: A MINLP-Based Preventive Maintenance Planning. IEEE Access.

[7] Darestani, Y. M., Shafieezadeh, A., & Cha, K. (2019). Effect of modelling complexities on extreme wind hazard performance of steel lattice transmission towers. Structure and Infrastructure Engineering, 1–18.

[8] Federal Emergency Management Agency (FEMA). (2009). FEMA P695: Quantification of Building Seismic Performance Factors. (Washigton, DC, USA), 421.

[9] American Society of Civil Engineers (ASCE). (2016). Minimum design loads for buildings and other structures. ASCE Manuals and Reports on Engineering Practice, No. 07 (Reston, VA).