Study on the High Wind Fragility Assessment for 154kV Transmission Tower using LHS

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***Keywords :** high wind, fragility assessment, transmission tower, latin hypercube sampling

1. Introduction

Currently, global attention is focused on the acceleration of climate change and its ongoing impacts. Natural disasters not only result in human casualties but also significantly affect the stability of structures. In particular, the safety of nuclear power plant (npp) structures is receiving significant attention. According to the investigation results from OPIS (Operational Performance Information System for Nuclear Power Plant), the primary cases of damage to npp structures have been predominantly attributed to high winds and typhoons accompanied by high winds [1].

In this paper, we studied on the methodology for wind fragility assessment specifically focusing on 154kV transmission towers. Transmission towers are crucial facilities for supplying power both internally and externally in power plants, including npp. To account for uncertainties in high wind fragility assessment, this paper considers the variability of structural materials and parameters of wind load. Wind directions are set at 90°, 0°, and 45° (yawed wind) with respect to the transmission line direction. The probability of failure for each wind speed is determined using the Latin Hypercube Sampling (LHS) technique. The wind fragility is then optimized through the least squares method, and the results are incorporated into a database using the log-normal cumulative distribution.

2. Assessment Method

2.1 Numerical Analysis Model

The numerical analysis model selected for this study corresponds to a 154kV transmission tower, representing the longest line length domestically. The numerical analysis was performed using the ABAQUS program, as illustrated in Fig. 1. The transmission tower has a height of 38.3m and a width of 6.8m. L-shaped Angle steel was used for the structural components. In addition to the self-weight of the structure, the dead loads of insulators, marker balls were applied as fixed loads. The material properties of the structural components are listed in Table I.

2.2 Wind load

Wind loads were referenced from ASCE 7-16 and the ASCE manual [2, 3]. As depicted in Fig. 2, wind directions of 90° (longitudinal direction), 0° (transverse direction), and yawed wind were considered. To account for yawed wind, two methods were employed. First, the wind face method, which applies loads directly to the structure face, and the wind on member method, which applies loads to each structural member, as illustrated in Fig. 2. The wind face method is emphasized here [3]. Fig. 3 illustrates the application of the wind face method. The wind loads on the transmission tower are expressed by Equation 1, and the wind loads on conductors and ground wires are represented by Equation 2.

$$\boldsymbol{F_t = QK_zK_{zt}V_{MRI}^2G_t\delta_\Psi(C_{ft}A_{mt}cos^2\Psi + C_{fl}A_{ml}sin^2\Psi)} \qquad (1)$$

$$\boldsymbol{F_w = QK_zK_{zt}V_{MRI}^2G_w\Psi(\ G_wAcos^2\Psi)} \qquad (2)$$

Here, $\boldsymbol{Q}$ represents the air density coefficient, $\boldsymbol{K_z}$ is the wind pressure exposure coefficient, , $\boldsymbol{K_{zt}}$ is the topographic factor, $\boldsymbol{G}$ is the gust factor, $\boldsymbol{C}$ is the force coefficient, $\boldsymbol{A}$ is the projected area, $\boldsymbol{\Psi}$ is the yaw angle, and $\boldsymbol{\delta}$ is the solidity factor.

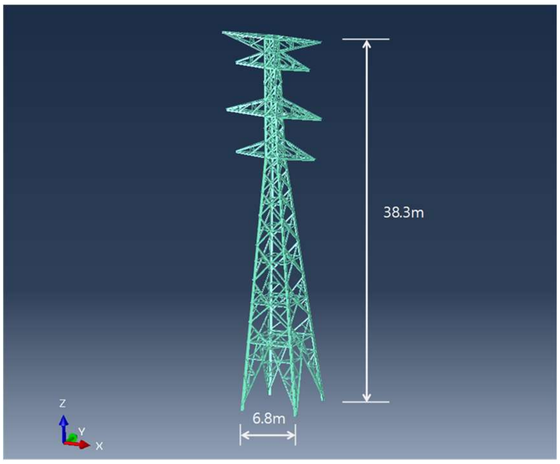


Fig. 1. 154kV transmission tower model in ABAQUS

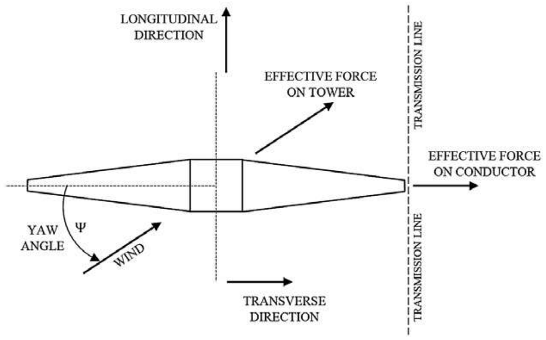
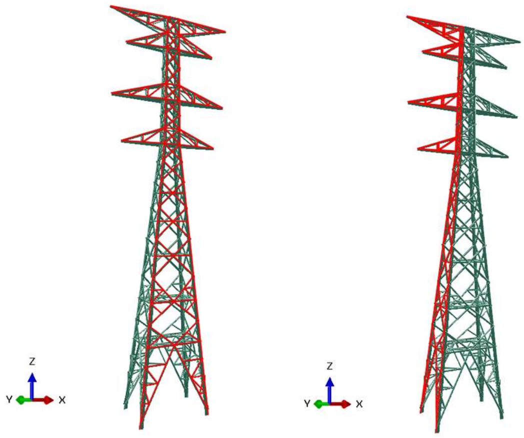


Fig. 2. Yawed wind on a transmission line



(a) 90°(longitudinal direction) (b) 0°(transverse direction)
Fig. 3. Face of wind face method

Table I: Specification of structural material

Standard		Elastic Modulus (MPa)	Density (ton/m^3)	Poisson's ratio
SS400	L 45 x 4	2.0E+5	7.850	0.3
	L 50 x 4			
	L 65 x 6			
	L 60 x 4			
	L 70 x 6			
	L 75 x 6			
	L 90 x 6			
	L 150 x 12			
SS540	L 90 x 7			
	L 100 x 7			
	L 120 x 8			
	L 130 x 12			
	L 150 x 12			
dead loads of insulators, marker balls		3.91 kN		

2.3 Statistics of the material and wind load parameter

The key element in the wind fragility assessment is considering uncertainty. The variability of coefficients for the structure's materials and parameters of wind load can be derived based on experiments, analyses from programs like HAZUS, or references. Table II lists the statistical values for structural materials [4, 5] and wind load variables [6] that can be applied in the wind fragility assessment through literature sources.

2.4 Simulation for fragility assessment

Fig. 4 depicts the simulation flowchart for conducting a wind fragility assessment on the transmission tower [7]. The flow of the methodology is as follows:

1. Selection of the target structure.
2. Definition of statistical values for parameters of wind load and structural materials.
3. Definition of the wind speed range.
4. Sample the population twice (as per step 2), calculate wind loads at the minimum wind speed defined in step 3, and then perform numerical analysis.
5. Check the failure of members.
6. Repeat steps 4 and 5 according to the specified number of samples to derive the probability of damage.
7. Increase the wind speed from the minimum defined in step 3 to the maximum, repeating steps 4 to 5.
8. Final check the probability of failure for each wind speed.

Simulation techniques, notably Monte Carlo Simulation (MCS) and Latin Hypercube Sampling (LHS), are commonly employed. For MCS, a higher number of samples enhances reliability. In contrast, LHS offers the advantage of performing analyses with a relatively small number of samples. In the case of wind fragility assessment, MCS typically applies more than 5,000 samples [8], while LHS applies 20 or more samples [9]. Consequently, for fragility assessments through calculations, MCS is deemed suitable; however, in this paper, considering the use of numerical analysis models, LHS is considered appropriate. The wind speed range is set from 10 to 80 m/s, exceeding the design load. For each wind speed, 100 samples are generated using the LHS technique, and numerical analyses are performed 7,000 times for each wind direction (90°, 0°, and 45°), resulting in a total of 21,000 numerical analyses.

2.5 Fragility curve

Before creating the fragility curve, Equation 3 represents the limit state function for wind fragility assessment.

$$G(R,\ W) = R - W \tag{3}$$

Here, **R** represents the resistance capacity, and **W** represents the wind load. This condition signifies the scenario where the wind load exceeds the resistance capacity, resulting in failure. In this paper, the yield strength of the steel is set as the resistance capacity.

The probability of failure obtained through LHS simulation can be optimized using either the least square method or the maximum likelihood estimation method. In this paper, the least square method was employed, as shown in Equation 4.

$$\widehat{m_R}, \widehat{\xi_R} = min \sum_{x=1}^{n} [P_f(v) - F_r(v)]^2 \tag{4}$$

Here, $\boldsymbol{P_f(v)}$ represents the failure probability of the transmission tower evaluated using the LHS technique, and $\boldsymbol{F_r(v)}$ is the discretized function optimized by the least square method.

To calculate the probability of failure for any given wind speed, the discrete function needs to be transformed into a continuous function. Equation 5 represents a log-normal cumulative distribution model for database transformation into a continuous function [7]. By applying the population mean and variance derived from Equation 4, the final fragility curve can be obtained.

$$F_r(y) = \Phi\left[\frac{\ln(y)-m_R}{\xi_R}\right] \qquad (5)$$

Here, $\boldsymbol{\Phi}$ is the standard normal distribution function, $\boldsymbol{m_R}$ is the logarithmic median of capacity, $\boldsymbol{\xi_R}$ is the logarithmic standard deviation of capacity.

Table II: Statistics of the material and wind load

Para-meter	Exposure Categories	Mean	COV	Type
K_z	B(h<4.6m)	1.17	0.19	N^1
	B(h≥4.6m)	$2.01(\frac{z}{366})^{2/7} * 1.01$	0.19	N
	C(h<4.6m)	1.36	0.14	N
	C(h≥4.6m)	$2.01(\frac{z}{274})^{2/9.5} * 0.93$	0.14	N
	D(h<4.6m)	1.52	0.14	N
	D(h≥4.6m)	$2.01(\frac{z}{213})^{2/11.5} * 0.99$	0.14	N
Yield strength (MPa)	SS400	263.7	0.07	LN^2
	SS540	429.0	0.07	LN
Elastic modulus(MPa)		2.06E+5	0.03	LN
Poison's ratio		0.3	0.03	LN

1 : Normal distribution
2 : Lognormal distribution

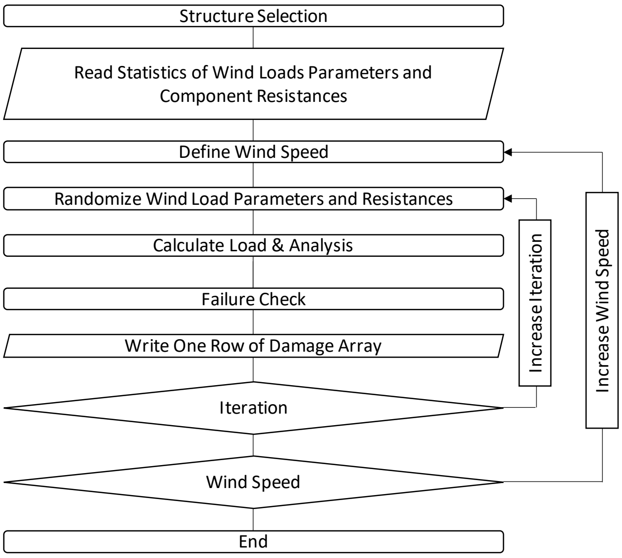


Fig. 4. Simulation flow chart for wind fragility assessment

3. Conclusion

This paper has reviewed the methodology for conducting wind fragility assessment, with the target structure being a 154kV transmission tower. Wind loads were calculated based on ASCE 7 standards, and the analysis was performed for wind directions of 90°, 0°, and 45° with respect to the transmission line direction. The wind face method was used for applying wind loads. In the LHS-based wind fragility assessment for the transmission tower, uncertainties were considered by incorporating variability in structural material and parameters of wind load. A total of 21,000 numerical analyses were conducted under these conditions. Data on wind speeds inducing fragility and initial failure of the transmission tower were derived, and the analysis of the current 21,000 data points is ongoing.

In future research, it is anticipated that this wind fragility assessment methodology can be applied to other structures or different natural disasters. It is considered necessary to incorporate major failure modes such as buckling failure and cut loss failure of the transmission tower for a detailed examination of wind fragility assessment.

4. ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20224B10200040).

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