13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Wind Reliability of Transmission Line Models using Kriging-Based Methods

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ABSTRACT: Risk assessment of power transmission systems against strong winds requires models that can accurately represent the realistic performance of the physical infrastructure. Capturing material nonlinearity, p-delta effects in towers, buckling of lattice elements, joint slippage, and joint failure requires nonlinear models. For this purpose, this study investigates the reliability of transmission line systems by utilizing a nonlinear model of steel lattice towers, generated in OpenSEES platform. This model is capable of considering various geometric and material nonlinearities mentioned earlier. In order to efficiently estimate the probability of failure of transmission lines, the current study adopts an advanced reliability method through Error rate-based Adaptive Kriging (REAK) proposed by the authors. This method is capable of significantly reducing the number of simulations compared to conventional Monte Carlo methods such that reliability analysis can be done within a reasonable time. Results indicate that REAK efficiently estimates the reliability of transmission lines with a maximum of 150 Finite Element simulations for various wind intensities.

1. INTRODUCTION

Electric power is transferred from power plants to distant areas through transmission systems, commonly supported by lattice towers. Although lattice towers are usually designed to withstand high intensity wind hazards, experience from past weather related events such as hurricanes, tornados, and downbursts has highlighted their vulnerability (Campbell, 2012; Hoffman and Bryan, 2013; Elawady et al., 2017). For example, Hurricane Irene (2011) caused 280 transmission line failures and hurricane Sandy (2012) led to 200 transmission line failures (Hoffman and Bryan, 2013). Moreover, as transmission lines perform with minimum redundancy, any failure can result in power outages for large geographical areas. For example, transmission line failures in Hurricane Irene (2011) and Hurricane Sandy (2012) resulted in 6.69 million and 8.66 customers to lose their power, respectively (Hoffman and Bryan, 2013).

A large percentage of current studies on performance assessment of transmission lines, assumed deterministic models for investigating failure in lattice towers (Jiang et al., 2011; Jiang et al., 2017; Ahmed et al., 2009). However, for risk management purposes, there is a significant need to estimate the reliability of transmission towers through probabilistic models that account for uncertainty in demand and capacity of lattice towers as well as various failure modes. There are a few studies that investigated the performance of lattice towers through probabilistic models

(Rezaei, 2016; Fu et al., 2016). However, as these studies use simplified models that do not account for post buckling and post yielding behavior of tower elements as well as joint slippage and joint failure behaviors, they are not necessarily representative of the true performance of lattice towers during high intensity wind hazards such as hurricanes. In these studies, it is assumed that any failure in the tower results in its total failure. However, as lattice towers are significantly indeterminate structures, they may not fail under a single failure unless there is a failure mechanism developed in the tower. To estimate the probability of failure of lattice towers, first order reliability methods have been used in the literature (Rezaei, 2016). However, first order reliability methods are not accurate when nonlinear behavior of steel elements (such as post buckling and post yielding behavior) is taken into account. Monte Carlo simulation methods can also be used to estimate the probability of failure of lattice towers. However, these methods require a large number of realizations to yield a reliable estimate of probability of failure of the system especially for small failure probabilities (Zamanian, 2016).

In order to address the aforementioned limitations, this study investigates the probability of failure of lattice transmission towers by developing a high fidelity Finite Element model that accounts for post buckling and post yielding behavior of steel elements. In addition, joint slippage and joint failure are modeled through a nonlinear connection model developed in OpenSEES (McKenna, 2000) Finite Element platform based on the model suggested by Ungkurapinan (2000). Subsequently, the probability of failure of a lattice tower is estimated through a set of pushover analyses along with an Error rate-based Adaptive Kriging (REAK) model developed by the authors (Wang and Shafieezadeh, 2018). This model can efficiently estimate the probability of failure with much less number of Finite Element simulations compared to ordinary Monte Carlo simulation methods. Such reliability models can be used in risk assessment procedures to enhance the resilience of power networks (Bhat et al., 2018; Darestani et al., 2016a; Darestani et al. 2016b; Darestani et al. 2017; Darestani and Shafieezadeh, 2017).

2. FINITE ELEMENT MODELING OF TRANSMISSION TOWERS

Due to various complexities such as post yielding and post buckling nonlinearities, joint slippage, and joint failure along with various modes of failure, high fidelity nonlinear Finite Element models are essential for a reliable estimation of the performance of transmission lines during high intensity wind hazards. For this purpose, a nonlinear static pushover analysis is employed in OpenSEES platform and elaborated in the following subsections.

2.1 Modeling Steel Lattice Elements in OpenSEES

In order to account for post yield elasticity, Steel01 material model is considered in OpenSEES, which assumes a bilinear relationship for stress-strain behavior. Nonlinear displacement-based beam column elements are defined through five integration points with 10 fiber sections along the height and three fiber sections along the width of angle elements at each integration point. In addition, p-delta effects and geometric nonlinearities are accounted for through a co-rotational geometric transformation. In order to consider buckling accurately, according to Uriz et al. (2008), each element is divided in half and a camber displacement equal to 1/2000 to 1/1000 of the length of the element is applied to the middle node.

2.2 Modeling Connections

Under strong wind loads such as hurricanes, there is a significant level of joint slippage in the connections. Joint slippage considerably increases the lateral displacement of the tower, which can result in additional p-delta effects and structural couplings between adjacent towers. Ungkurapinan (2000) suggested a nonlinear model for joint slippage behavior based on a set of experiments he performed for steel angle members. The proposed model follows a backbone curve similar to Fig.1. This study adopts this model to consider joint slippage behavior. For this purpose, joint slippage is modeled by assigning zero-length elements in OpenSEES at the connections and applying the joint slippage behavior to the zero-length elements as a material model (Fig. 2)

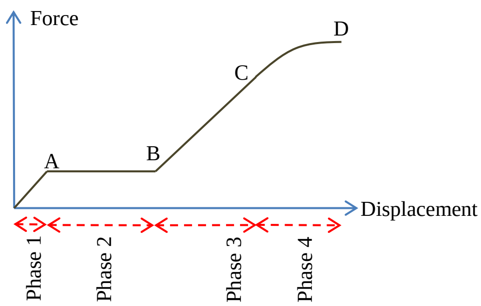

Figure 1. Backbone curve of slippage behavior (Ungkurapinan, 2000)

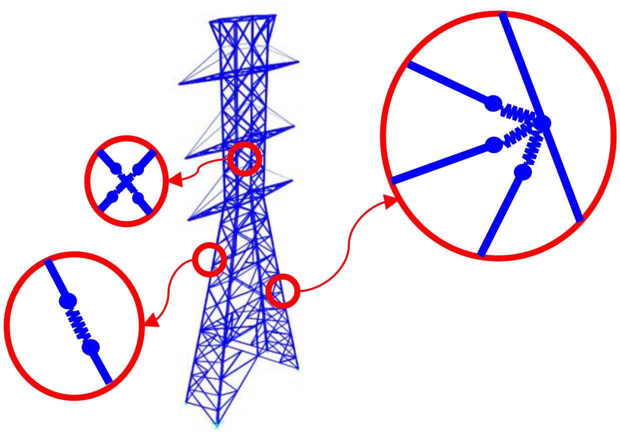

Figure 2. Modeling joint slippage behavior in OpenSEES using zero-length elements.

3. WIND LOAD ON LATTICE TOWERS

To estimate the wind induced load on lattice towers, the static gust wind load suggested by ASCE07 (2016) is employed in this study. ASCE07 proposes the following equation for calculating wind induced load on non-building structures.

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

where q_z is the velocity pressure at height z on the tower, G is the gust-effect factor, C_f is the force coefficient, and D is the width of the element perpendicular to the wind direction. q_z is estimated from:

$$q_z = 0.613 K_z K_d K_{zt} K_e V^2 \tag{2}$$

where 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 3-second gust wind velocity at 10 m above the ground line. Since the assumed lattice tower is located in a flat area, therefore, K_{zt} is equal to 1. K_z is is obtained from

$$K_z = 2.01 \left(\frac{\max(4.75, z)}{z_g} \right)^{2/\alpha} \tag{3}$$

where z is the height from the ground. Since the lattice tower is located in an open terrain area, exposure category is C, and α and z_g are 9.5 and 274.32 m, respectively. The wind directionality factor, K_d, is equal to 1. The gust-effect factor, G is equal to 0.85. ASCE07 (2016) defines the force coefficient, C_f , for squared trussed towers as

$$C_f = 4 \in^2 - 5.9 \in + 4 \tag{4}$$

where $\in$ is the ratio of solid area to gross area of the tower face under consideration. C_f is equal to 1, for the conductors (ASCE 74, 2009).

4. RELIABILITY ANALYSIS USING REAK METHOD

As it was mentioned previously, reliability analysis of lattice towers requires estimation of the limit state function for a large number of realizations of uncertain parameters to perform a Monte Carlo simulation. However, as nonlinear Finite Element analysis is computationally expensive and considerably time consuming, direct estimation of limit state function for the entire set of realizations is practically impossible (Ebad-Sichani et al. 2019; Ebad-Sichani et al. 2018; Fereshtehnejad et al., 2016). In order to address this limitation, various reliability analysis methods based on Kriging have been developed in the literature (Echard et al. 2011; Jones et al., 1998; Wen et al., 2016; Wang and Shafieezadeh, 2018). In Kriging-based reliability analysis, estimation of the limit state function using computationally expensive Finite Element method is limited to a small number of candidate realizations, in which the limit state function ($G(x)$) is close to zero. Subsequently, a Kriging model is used to estimate the limit state function for the entire set of realizations of uncertain parameters to efficiently perform a Monte Carlo simulation. Therefore, using Kriging-based reliability analysis, a large number of Finite Element simulations are avoided and subsequently, the probability of failure of lattice towers are efficiently estimated. Further discussion on limitations of different Kriging-based reliability analyses can be found in the paper by Wang and Shafieezadeh (2018).

In this study, in order to obtain the probability of failure of lattice towers, the Error rate-based Adaptive Kriging (REAK) proposed by the authors (Wang and Shafieezadeh, 2018) is adopted. This method has shown two advantages over the existing adaptive Kriging reliability methods. First, this method introduces an effective adaptive sampling region, in which the points with low joint probability density function are removed from candidate samples. Second, an upper bound for the rate of error is introduced based on the Lindeberg's condition for the Central limit Theorem (CLT). Using this upper bound, a faster convergence can be obtained for the reliability analysis. In the following, REAK algorithm is summarized:

Step 1: Generate N realizations of uncertain parameters using Latin Hypercube Sampling method.

Step 2: Define an effective sampling region as

$$P_{\{\rho(x)>\rho_{thr}\}} = \alpha \hat{P}_f^{n-1}. \qquad (4)$$

where $\rho(x)$ is the joint probability density of candidate design samples, α is a constant coefficient and $\hat{P}_f^{n-1}$ is the probability of failure achieved by Kriging model. Points outside this region will be later removed from training samples.

Step 3: Randomly select a small number of initial points from Step 1. These points will be used for constructing the initial Kriging model.

Step 4: Construct a Kriging model for estimating the limit state function using Finite Element analysis of lattice tower.

Step 5: Update the efficient sampling region using Eq. (4).

Step 6: Among the samples that satisfy Eq. (4), choose the one with the maximum EFF from the following Eq.:

$$\begin{gathered} EFF(\boldsymbol{x}) = (\mu_K(\boldsymbol{x}) - a) \times \\ \left[2\Phi\left(\frac{a-\mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right) - \Phi\left(\frac{a^- - \mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right) - \Phi\left(\frac{a^+ - \mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right)\right] \\ -\sigma_K(\boldsymbol{x}) \times \\ \left[2\phi\left(\frac{a-\mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right) - \phi\left(\frac{a^- - \mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right) - \phi\left(\frac{a^+ - \mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right)\right] \\ +2\sigma_K(\boldsymbol{x})\left[\Phi\left(\frac{a^+ - \mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right) - \Phi\left(\frac{a^- - \mu_K(\boldsymbol{x})}{\sigma_K(\boldsymbol{x})}\right)\right] \end{gathered} \qquad (5)$$

where $\phi(\cdot)$ denotes the standard normal probability density function and $\Phi(\cdot)$ is the standard normal cumulative density function, $a = 0$, $a^+ = 2\sigma_K(\boldsymbol{x})$, and $a^- = -2\sigma_K(\boldsymbol{x})$. $\mu_K(\boldsymbol{x})$ and $\sigma_K(\boldsymbol{x})$ are the mean and standard deviation of Kriging prediction for point x, respectively.

Step 7: If $max(EFF)$<0.001 go to step 8 otherwise go to step 4.

Step 8: Check if the upper bound of error rate ($\hat{\epsilon}_{max}$) is less than 0.05

$$\hat{\epsilon}_{max} = \max_{I_{\Omega_2} \in N^R_{\Omega_2^f}} \left(\left| \frac{N_{\Omega_2^{\hat{f}}} - I_{\Omega_2}}{N_{\Omega_1^{\hat{f}}} + I_{\Omega_2}} \right| \right) < 0.05 \qquad (5)$$

where Ω_1 and Ω_2 are the regions inside and outside of the effective sampling region denoted by Eq. (4), respectively. N denotes the size of the set, and I is an indicator that takes one when the sign of the limit state function is estimated wrongly and takes zero when the sign of the limit state function is estimated correctly.

Step 9: If $\hat{\epsilon}_{max}$<0.05 is not satisfied, increase the size of the effective sampling region by reducing the value of α.

Step 10: Estimate the coefficient of variation of failure probability

$$COV_{P_f} = \sqrt{\frac{1-\hat{P}_f}{\hat{P}_f N_{MCS}}} \qquad (5)$$

Step 11: If $COV_{P_f} < 0.05$, stop the process, otherwise, increase the number of LHS samples.

A flowchart of REAK algorithm is provided in Fig. 3. As it was mentioned, REAK algorithm has a better efficiency compared to the existing adaptive Kriging reliability methods as it provides an adaptive effective sampling region denoted in Step 2 and an upper bound for the maximum error rate presented in Step 6.

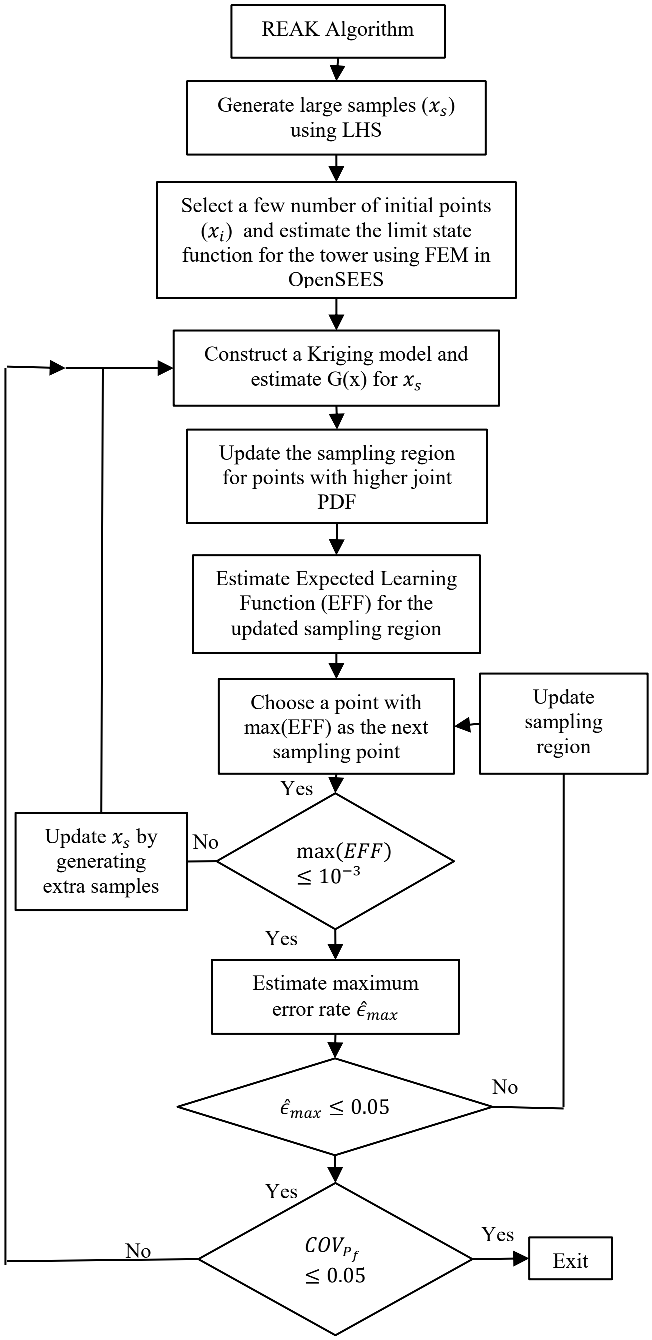

Figure 3. REAK algorithm

5. NUMERICAL ANALYSIS

As it was noted previously, lattice towers experience complex nonlinear behaviors at the prior to and at the verge of failure especially under strong winds. These complexities stem from post yielding and post buckling nonlinear behavior of steel elements, joint slippage and joint failure, uncertainties in demand and capacity as well as various modes of failure. Due to these complexities, Finite Element analysis methods are necessary to estimate the performance of lattice towers. However, estimation of reliability of lattice towers through conventional Monte Carlo simulation methods requires a large number of time consuming evaluations of limit state functions, which makes the process of reliability analysis practically impossible. For this purpose, in this study, a reliability analysis through Error rate-based Adaptive Kriging is adopted to efficiently generate a fragility model for a double circuit vertical steel lattice tower. This tower is 27.4 m tall, located in a hurricane prone coastal area in south of the United States. It carries 6 lines of Drake ACSR (Aluminum Reinforce Steel Conductors) and two line of Optical Ground wires (OPGW). The span length is 258 m and it is assumed that multiple spans with similar properties exist in the system. Therefore, the impact of structural couplings is negligible (Darestani et al., 2016a; Darestani et al. 2016b; Darestani et al. 2017). A sketch of the modeled tower is provided in Fig. 4.

Figure 4. The assumed double circuit vertical steel lattice tower

The tower is modeled in OpenSEES platform as it was discussed in sections 2 and 3. In order to perform the reliability analysis, uncertainty in material and demand should be considered. Cha et al. (2018), performed a sensitivity analysis on various uncertainties in modeling of the current lattice tower and they found the parameters provided in Table 1 as significant uncertain parameters that can affect the performance of the lattice tower. Therefore, in this study, the parameters shown in Table 1 are assumed uncertain. The other parameters are set to their mean value.

In order to perform the reliability analysis, a limit state function should be defined for the tower. In this study, a pushover analysis is carried out to obtain the maximum load bearing capacity of the tower. The load bearing capacity is defined as a factor of design wind speed. For the current tower, the design wind speed is equal to 130 mph. Subsequently, the limit state function for the tower is defined as:

$$G(x) = F_L - 1 \quad (5)$$

where F_L is the failure load factor presented in Fig. 5.

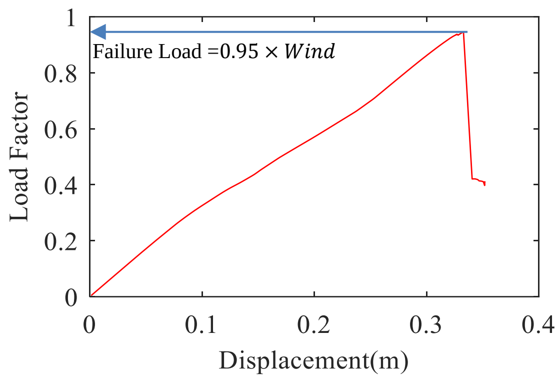

Figure 5. Definition of limit State function through pushover analysis

For the analysis performed in this figure, the failure load equals 0.95, which shows that any wind load greater than 0.95 times the design wind load of the tower results in the failure of the tower.

Using REAK method a fragility model is developed for the double circuit vertical lattice tower (Fig. 5). The results highlight that the probability of failure of lattice transmission towers can be efficiently estimated through REAK. For the assumed lattice tower, the number of calls to estimate the limit state function through Finite Element analysis is less than 150. Comparing this value with conventional Monte Carlo simulations which require tens of thousands of simulations highlights the efficiency and importance of adaptive Kriging reliability methods such as REAK to generate fragility models for lattice towers. The fragility analysis explained in this paper can be integrated with a Generalized Linear Model (GLM) to provide simple and accurate fragility models for transmission towers with different configurations including, type, height, span length, and number and diameter of conductors, among others. A similar approach was used by the authors in (Darestani and Shafieezadeh, 2019) to generate multi-dimensional wind fragility functions for wood utility poles.

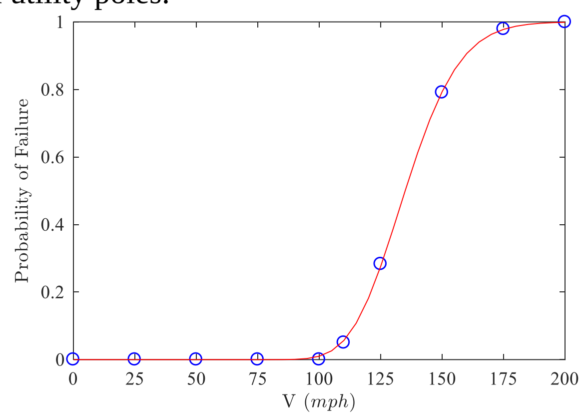

Figure 6. Fragility model developed for the double circuit vertical lattice tower using REAK method

Table 1: Uncertain parameters assumed for reliability analysis

Properties		Notation	Type of Distribution	Mean	COV	Reference
Steel material	Modulus of elasticity	$\boldsymbol{E}$	LogNormal	2.0e11 (N/m^2)	0.06	ASCE07 (2010) and ASCE 74 (2009)
	Yield stress of main leg	$\boldsymbol{f_{ym}}$	LogNormal	4.02e8(N/m^2)	0.1	
	Yield stress of bracing members	$\boldsymbol{f_{yb}}$	LogNormal	2.9e8 (N/m^2)	0.1	
	Post yield elasticity	$\boldsymbol{E_{st}}$	LogNormal	0.02E(N/m^2)	0.25	
Wind load	Gust effect factor	$\boldsymbol{G}$	Normal	Section 3	0.11	Ellingwood and Tekie (1999)
	Force coefficient	$\boldsymbol{C_f}$	Normal	Section 3	0.12	
	Velocity pressure exposure coefficient	$\boldsymbol{K_z}$	Normal	Section 3	0.16	
	Wind directionality factor	$\boldsymbol{K_d}$	Normal	Section 3	0.08	
Connection Type B	Slippage length	Phase 2	Uniform	0.45(mm)	0.15	Ungkurapinan (2000)

3. SUMMARY AND CONCLUSIONS

Complex behavior of lattice towers during strong wind necessitates use of Finite Element analysis methods. The complexities stem from post yielding and post buckling nonlinear behavior of towers, joint slippage and joint failure, and various modes of failure that can occur in a lattice tower, among others. Given that conventional Monte Carlo simulation methods require a large number of time consuming Finite Element simulations to estimate the probability of failure accurately, Monte Carlo simulation methods cannot be directly used.

In order to address this limitations, this study, considers the impact of post yielding and post buckling through a bilinear material model integrated with a displacement beam column element modeled in OpenSEES Finite Element platform, in which each element is divided in half and a camber displacement is applied to the mid-node to capture the out of plane displacement of steel elements under buckling effects. In order to consider p-delta effects and instability caused by buckling effects large deformations are accounted for through a co-rotational geometric transformation in OpenSEES. In addition, joint slippage and joint failure are accounted for through a nonlinear experimentally validated model applied to each connection through zerolength elements in OpenSEES. Second, to estimate the probability of failure of the lattice tower, a reliability analysis through Error rate-based Adaptive Kriging (REAK) is employed in this study. REAK has two advantages compared to previous adaptive Kriging reliability analysis methods. First, it defines an adaptive effective sampling region that neglect realizations with low joint probability density function, and second, it defines an upper bound for the rate of error, through which the convergence is obtained much faster. Using REAK a fragility model is developed for a double circuit vertical lattice tower. The result indicate that for various wind speeds, especially for those with low probability of failure, REAK can efficiently estimate the probability of failure. The number of calls to estimate the limit state function through Finite Element analysis is less than 150, which highlights the efficiency of the method, considering the high accuracy of the results.

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