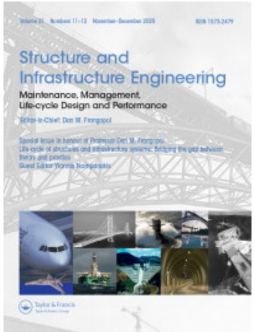

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Probabilistic analysis of wind-induced failures of transmission tower-line systems

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ABSTRACT

Wind loading on a transmission tower structure is affected by the wind field, structural parameters, and the geo-spatial arrangement of the transmission line. This research develops a probabilistic wind-induced performance evaluation framework for transmission tower-line systems by incorporating the effects of wind speed and direction, along with the transmission line orientation. Based on a practical transmission tower-line system in Australia, the system level failure probability of an angled tower-line system, as well as an all-straight tower-line system are calculated by considering various spatial/non-spatially distributed structural and wind field parameters. To boost the computational efficiency by 70%, an adaptive virtual modeling surrogate model as well as a novel polynomial kernel is developed to approximate the system limit state functions when incorporating all sources of structural uncertainties. A sensitivity analysis is implemented to identify critical aerodynamic parameters toward accurate fragility assessment. Comparison studies between all-straight tower-line and angled tower-line system have been conducted to discuss the effects of spatial variabilities, correlation lengths, and wind attack angles toward system fragility. It was found that angled tower-line systems are up to 140% more vulnerable than an all-straight tower-line, and considering spatial variability of tower material properties increased vulnerabilities by 10-20%.

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Transmission tower-line system; fragility assessment; probabilistic analysis; wind-resistant capacity; uncertainty quantification

1. Introduction

Overhead power transmission networks play a crucial role in the delivery of electrical energy in modern society. These networks, composed of lattice steel towers, insulators, and conductors, form transmission tower-line systems, which are characterized by long spans, high flexibility, and strong non-linear behavior, making them vulnerable to wind forces (Shafieezadeh et al., 2014). Any damage or failure to components within this system can compromise its stability and safety, leading to significant economic and social losses (Bocchini et al., 2014). On 31 January 2020, six transmission towers collapsed during a high wind event in Victoria, Australia (Victoria, 2022) and on 17 October 2024, a storm brought down seven transmission towers leaving 20,000 people in Broken Hill in outback New South Wales, Australia and its surrounds without power for nearly two weeks (ABC News, 2024). With the growing demand for electricity, transmission tower-line systems are rapidly expanding, with taller towers, longer transmission lines, and larger insulators being constructed worldwide. For example, in Australia, 10,000 km of new transmission lines are needed for the Integrated System Plan at a cost of $20 billion to modernize electricity grid and deliver new and upgraded transmission infrastructure (Government, 2024).

Despite wind loads being factored into design standards and codes, there are still frequent instances of damage or power outages caused by wind events (Ma et al., 2020, 2022). Lattice towers, for example, tend to undergo significant deformation during extreme winds, which is a leading cause of tower collapse. Additionally, the layout of transmission tower-line systems with either all-straight-lines or angled lines would also affect the most vulnerable directions of tower against strong wind loads. Therefore, it is critical to thoroughly assess the fragility performance of transmission tower-line systems in real-world wind conditions, focusing on both structural safety and operational reliability (Darestani et al., 2020; Darestani & Shafieezadeh, 2019).

Transmission towers have been the subject of extensive research due to their higher failure rates compared to other steel structures. For instance, detailed frameworks have been proposed to assess how hurricanes affect power system reliability (Darestani et al., 2018), identify vulnerable sections of the network (Zhang et al., 2020), and analyze structural performance (Xue et al., 2020). Reliability-based design optimization approaches for transmission towers using genetic algorithms (Mathakari et al., 2007) and Bayesian optimizations (Lin et al., 2023) have been introduced. Researchers have also investigated the uncertainties in wind turbulence and structural capacities, stressing the importance of these uncertainties in fragility analysis (Bjarnadottir et al., 2013; 2014). At the structural member level, specifically regarding transmission towers and conductors, most previous studies

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have largely concentrated on the structural safety of a single tower structure, while the probabilistic risk assessment of tower-line system layout patterns under various wind attack angles has received less attention. One of the most common and serious issues for transmission lines in windy conditions is their seemingly random collapse, which is often related to line orientation. This type of accident poses a significant threat to the serviceability of power transmission networks, making it essential to more thoroughly evaluate the risks associated with tower-line orientations in extreme wind environments (Zheng et al., 2019).

To accurately predict and determine the actual probability of structural failure, it is important to simultaneously account for both the hazard occurrence probability and the fragility results across different damage limit states (Dehghani et al., 2021; Mousavi et al., 2024; Roman et al., 2024). As for structural members, most studies have utilized random variable-based representations to simulate the random physical/mechanical information of tower-line system (Deoliya & Datta, 2000; Ierimonti et al., 2017). However, the spatial correlations among various steel members are not well captured (Bocchini et al., 2011), which may overestimate the system integrity against strong wind attacks.

In light of the challenges described above, this research proposes a probabilistic wind-induced performance evaluation framework for transmission tower-line systems by incorporating the wind effects. The innovative contributions of this study are listed as follows: (1) The probabilistic wind-induced performance of an angled transmission tower-line system is freshly investigated and compared with an all-straight tower-line system, considering the effects of line orientations. (2) A random field probabilistic modeling approach that explicitly incorporates spatial correlations in material properties (i.e., Young's modulus, yield strength). (3) A new virtual modeling technique that helps to simulate the fragility functions of transmission tower-line system by using advanced machine learning algorithms, which greatly reduces the computational costs through the evaluation process. A case study of a practical transmission tower-line system in Australia illustrates that the proposed framework can support better decision-making, risk mitigation, and retrofitting strategies for tower-line operators.

2. Probabilistic fragility assessment framework

2.1. Structural modeling with material/geometric nonlinearity

This research proposes a probability-based wind fragility assessment framework for practical large-scale structures. The fundamental procedures contained within the framework is demonstrated in Figure 1.

Appropriate and accurate structural modeling is essential for fragility analysis (Bruneau et al., 2003; Melchers & Beck, 2018). For most transmission towers made of lattice steel, under certain strong wind conditions, the plasticity-involved large deformation would be inevitable for structural members (Feng et al., 2020; Liu et al., 2023; Sett et al., 2007). To appropriately tackle elastic-plastic yielding prior to ultimate failure, the considerations of both material and geometric nonlinearity especially for tall and slender structures like transmission towers are needed, which is defined by:

$$(\mathbf{K}_{ep} + \mathbf{K}_g)\Delta\mathbf{U} = \mathbf{F}_{ex} - \mathbf{R}_{in} \tag{1}$$

where $\mathbf{K}_{ep} = \int_V \mathbf{B}^T\mathbf{D}_{ep}\mathbf{B}dV$ and $\mathbf{K}_g = \int_V \mathbf{B}_g^T\mathbf{D}\mathbf{B}_g dV$ denote the elastoplastic stiffness matrix and geometric stiffness matrix, respectively. $\Delta\mathbf{U}$ denotes the incremental displacement vector as the combination product of the external force $\mathbf{F}_{ex}$ and the internal reaction force $\mathbf{R}_{in}$.

Considering the geometric nonlinear effects, structural element buckling is also captured for $\mathrm{P} - \Delta$ effects and large deformations in ABAQUS. Thus, in the proposed framework, the geometric elastoplastic buckling analysis is applied for the transmission tower structure and the displacements of the top of tower are collected as observation samples to evaluate structural nonlinear behaviors. The amplitudes of the acquired displacements can be classified into various levels to define different damage states of the tower structure, which are highly related to the surrounding wind environment and structural configurations. These considerations form a preliminary basis for performance and fragility assessment of transmission towers.

2.2. Probabilistic wind load simulation

The wind environment can be characterized by AS/NZS 7000: 2016 *Overhead line design* (Standards Australia/NewZealand, 2016), where the design site wind speed is:

$$V_{\mathrm{sit},\beta} = V_R M_d M_{z,cat} M_s M_t \tag{2}$$

where $M_{z,cat}$ is gust wind speed multiplier for terrain category at height z of a typical Australian tower in Figure 2, M_d is wind direction multiplier, M_s is shielding multiplier, M_t is topographic multiplier and V_R is basic regional 0.2s gust wind velocity for the region corresponding to a selected return period.

For lattice towers that are essentially square or rectangular in plan the force in the direction of the wind on the whole tower section is (Standards Australia/NewZealand, 2016):

$$F_m = q_z C_d A_m \tag{3}$$

where $q_z = 0.6V_{\mathrm{sit},\beta}^2 \times 10^{-3}(\mathrm{kPa})$ is the design pressure relying on wind speed, A_m is simplified member area, C_d is drag force coefficient.

2.3. Wind fragility model

The next step after acquiring the probabilistic responses is to evaluate the wind fragility of tower structure under various wind attack angles, as well as the line orientations. It is defined that once the structural response has exceeded the damage states or the threshold values, a failure event is determined to occur for the system. For a typical transmission tower-line system, the wind fragility is:

$$F_x = P_f(U \geq DS_x^{v,\theta}) \tag{4}$$

where $P_f(\cdot)$ is the probability of failure for tower-line structure by tower top displacement U exceeding the defined xth damage state DS_x, which is dependent on wind speed v and wind direction θ.

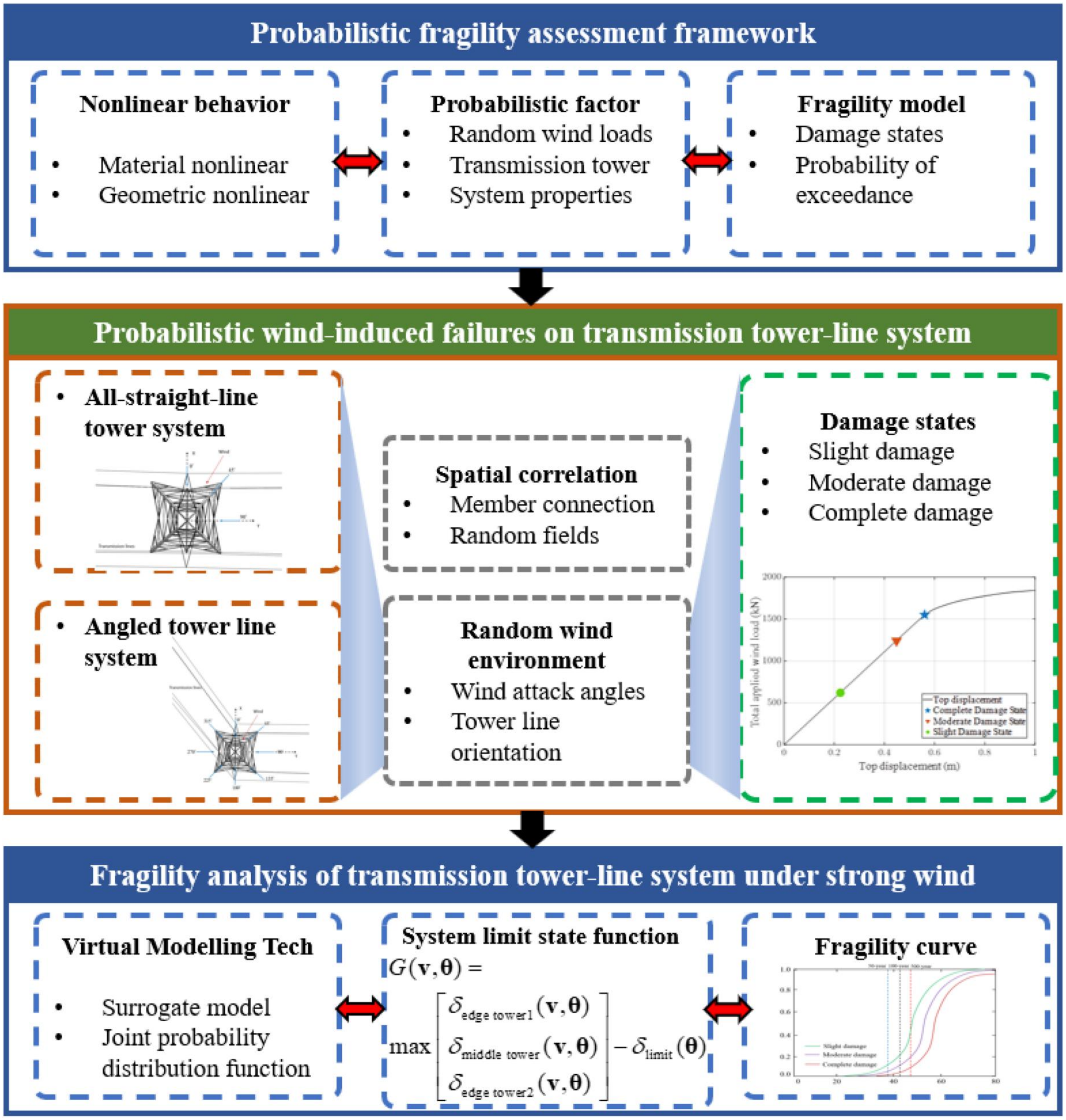


Figure 1. Probabilistic fragility assessment framework.

Based on the wind fragility model, the proposed framework establishes a relationship between the probability of wind hazards and the vulnerability of the structure, allowing for a dependable assessment of performance and the identification of the optimal orientation for a transmission tower-line system in a local complicated wind environment. The following sections apply this approach to an Australian transmission tower-line system.

3. Fragility analysis of transmission tower-line system

3.1. Modeling spatial dependent uncertainties

There are a number of uncertainty sources involved in the fragility analysis of a transmission tower-line system subjected to wind excitations, mainly including the applied wind loads, structural geometric dimensions, connections, and material properties. Variability in any of these sources will cause uncertainties in the structural demand and capacity. To tackle this issue, it is critical to consider the spatial correlations among the various segments of the tower structure, while pairwise correlation models provide a local measure of dependence between tower structural elements, they fail to efficiently capture the global spatial structure of a random field. For large-scale structures, this would also lead to a computationally intractable problem due to the cost of storing and inverting large covariance matrices. The Karhunen-Loève Expansion offers an optimal low-dimensional representation that maintains smooth variations across the structure, ensures statistical consistency, and significantly reduces computational cost. Thus,

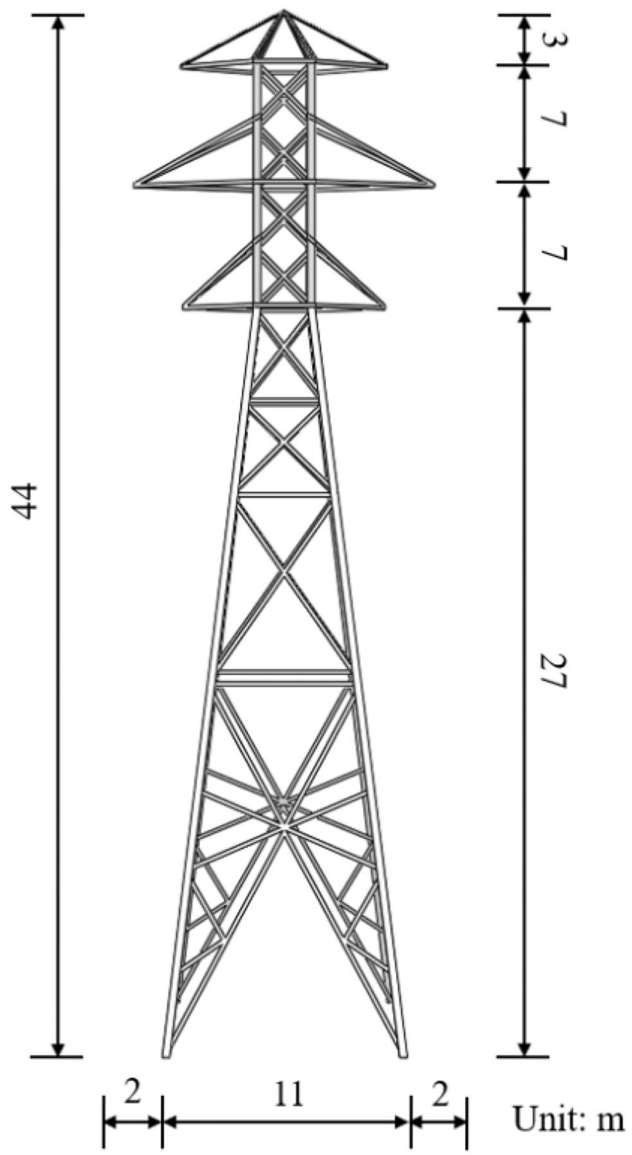


Figure 2. Configuration of the transmission tower (Government, 2023).

the Karhunen-Loève expansion-based generalized random field is used to represent the correlated member behaviors as:

$$\hat{\xi}(\mathbf{x},\chi) = \mu_{\xi}(\mathbf{x}) + \sum_{i=1}^{M}\sqrt{\gamma_i}\zeta_i(\chi)\phi_i(\mathbf{x});\ \mathbf{x}\in\Omega_2 \quad (5)$$

where $\mu_{\xi}(\mathbf{x})$ denotes mean value of the tower segment's property in the random spatial field $\hat{\xi}(\mathbf{x},\chi)$, $\zeta_i(\chi)$ is a group of M random variables needed to construct the random field, γ_i and $\phi_i(\mathbf{x})$ are the eigenvalues and eigenfunctions of the exponential covariance kernel function as follows:

$$\kappa(\mathbf{x}_1,\mathbf{x}_2) = \exp\left(-|x_1 - x_2|/l_x - |y_1 - y_2|/l_y\right) \quad (6)$$

where l_x, l_y are the correlation length parameters. By using the above random field function, different system field properties of transmission tower-line system can be correlated. Details of modeling spatial dependent uncertainties can be found in the following practical application section.

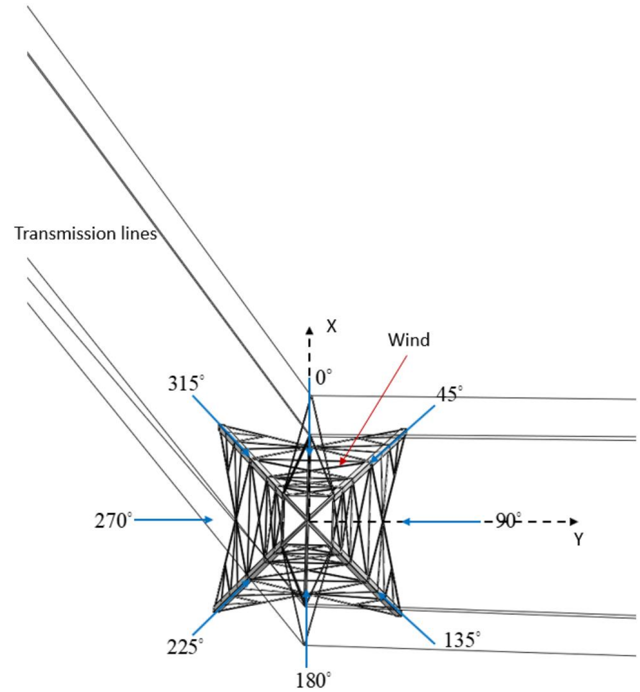


Figure 3. Wind attack angles for angled tower line system (plan view).

3.2. Fragility analysis of transmission tower-line system incorporating line orientations

Different wind attack angles and tower line orientations will result in different tower system fragilities. In this section, the effects of wind attack angles, as well as line orientation toward the response of tower-line system are considered, and two different conditions including (i) angled tower-line system, and (ii) all-straight-line tower system have been established for assessment.

First, for angled tower-line system: The angled tower-line structures are used in power transmission and distribution systems for several key reasons: (i) change of direction, (ii) terrain adjustments, (iii) urban planning and land use, and (iv) system design flexibility. To consider the wind induced structural response and reliability of an angled tower line system, eight wind attack angles (i.e., 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) need to be considered herein to perform comprehensive fragility analyses, as in Figure 3.

Second, for an all-straight-line tower system: Owing to the biaxial symmetry of the all-straight-line tower system, only three wind attack angles (i.e., 0°, 45°, and 90°) need to be considered herein to perform comprehensive fragility analyses, as in Figure 4.

3.3. Transmission tower-line system damage states

The peak values of the tower top displacement will be computed and used as a damage state indicator for the fragility assessment of the tower-line system. The three damage states were acquired under the condition that all structural properties were considered as nominal values. In practical engineering, there are inevitable deviations of properties around nominal values, the purpose of doing this it to investigate the probability of a tower-line system reaching a

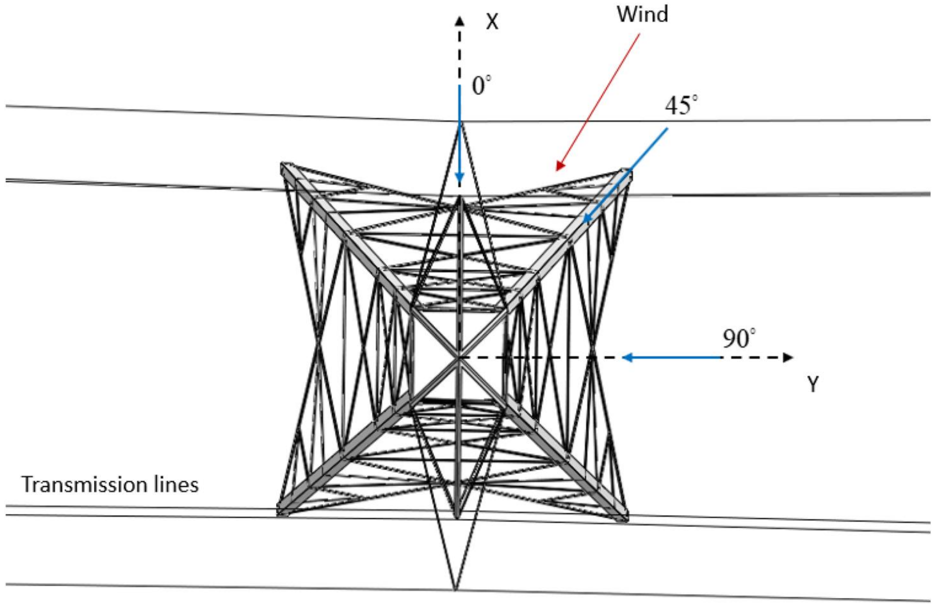


Figure 4. Wind attack angles for all-straight-line system (plan view).

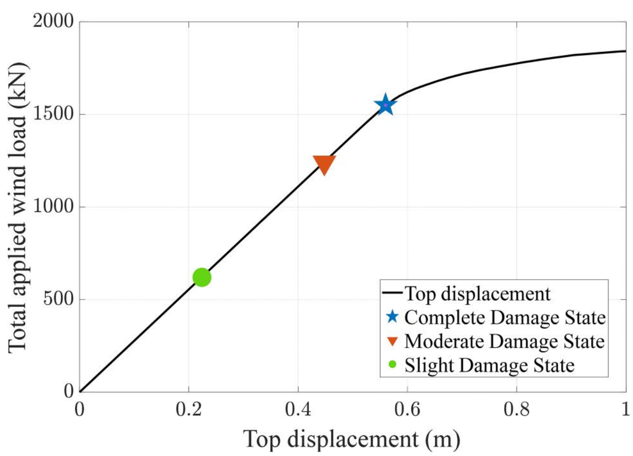


Figure 5. Damage states for transmission tower.

certain threshold. For the transmission tower, the three damage states are slight damage (SD1), moderate damage (MD2), and complete damage (CD3). CD3 occurs when over 90% of all frame and connection members experience yielding and buckling failure, thus losing its capacity to support the tower-line system (Wang et al., 2022). This occurs when the tower top displacement exceeds 0.585 m. The member and connection failure percentages are over 60%, 30% corresponding to top displacements 0.468 m, 0.234 m for MD2 and SD1, respectively. By monotonically increasing the horizontal wind loads on a single tower, the nonlinear static pushover curve of the tower along longitudinal directions, as well as three damage states are obtained, is illustrated in Figure 5.

It is observed that under different wind attack angles, the damage state displacements of towers will slightly differ. This is due to different angles cause variations in drag and lift forces acting on the members of the tower, and the effective area of the tower exposed to wind changes, altering the resulting forces and the corresponding peak displacement to change. The tower top displacements corresponding to the damage limit states under various wind attack angles are listed in Table 1.

3.4. Virtual modeling aided fragility analysis technique

To fully make use of various collected data, a newly developed virtual modeling technique can identify the inherent relationship between environmental inputs and structural response (Feng, Wang, Chen et al., 2023; Feng, Wang, Yu et al., 2023; Feng et al. 2024), so as to develop a robust surrogate model for the system reliability performance that can predict structural fragility in an efficient manner.

For the input and output vectors of $\mathbf{x}$ and $\mathbf{y}$, the virtual modeling creates a hyperplane to describe the relationship between the datapoints:

$$\hat{f}(\mathbf{x}) = \mathbf{k}(\mathbf{x})(\mathbf{p}_k - \mathbf{q}_k)^T - \hat{\mathbf{e}}_k^T \hat{\mathbf{G}}_k \mathbf{u}_k^* \tag{7}$$

where $\mathbf{k}(\mathbf{x})$ is the kernel-induced random vector for the inputs, $\mathbf{p}_k, \mathbf{q}_k \in \Re^n$ are the two positive kernelized hyperplane coefficients, $\mathbf{u}_k^*$ is the concerned optimal solution, matrix $\hat{\mathbf{G}}_k$ and vector $\hat{\mathbf{e}}_k^T$ are:

$$p_k, j = \begin{cases} 0, & w_j \le 0 \\ w_j, w_j > 0 \end{cases}, \quad q_{k,j} = \begin{cases} -w_j, & w_j < 0 \\ 0, & w_j \ge 0 \end{cases}, \quad j = 1, \ldots, n \tag{8}$$

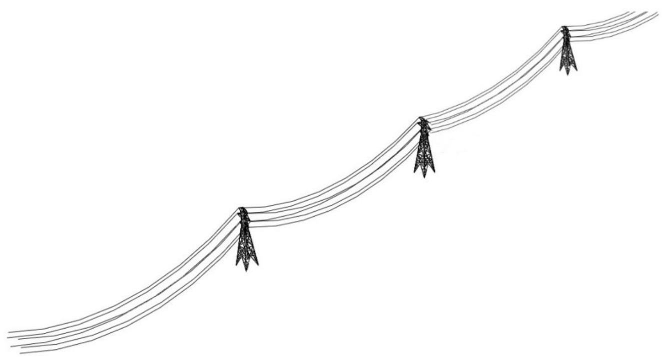
$$\hat{\mathbf{G}}_k = \begin{bmatrix} \mathbf{0}_{2m\times 2m} & \mathbf{0}_{2m\times m} & \mathbf{0}_{2m\times m} \\ \mathbf{0}_{m\times 2m} & \mathbf{I}_{m\times m} & \mathbf{0}_{m\times m} \\ \mathbf{0}_{m\times 2m} & \mathbf{0}_{m\times m} & -\mathbf{I}_{m\times m} \end{bmatrix}, \quad \hat{\mathbf{e}}_k = \begin{bmatrix} \mathbf{0}_{2m} \\ \mathbf{e}_m \\ \mathbf{e}_m \end{bmatrix} \tag{9}$$

where $\mathbf{I}_{m\times m} \in \Re^{m\times m}$, $\mathbf{e}_m = [1, 1, \ldots, 1]^T \in \Re^m$. The ultimate regression performance of the virtual modeling model depends on the kernel function selected, and a new type of feature mapping kernel function, namely the Dirichlet

Table 1. Limit states of the top displacement of the tower (unit: m).

Wind attack angles	Slight damage (SD1)	Moderate damage (MD2)	Complete damage (CD3)
0°	0.234	0.468	0.585
45°	0.201	0.402	0.502
90°	0.213	0.426	0.533

(a)



(b)

Figure 6. FE numerical transmission tower-line: (a) angled, (b) all-straight.

feature mapping is proposed, which is:

$$\varphi_d^\alpha(\mathbf{x}) = \begin{cases} x_d, & x_d \in \mathbf{x},\ d = 1, 2, \ldots, n \\ \dfrac{\Gamma(\sum_{k=1}^{n} \alpha_k)}{\prod\limits_{k=1}^{n} (\Gamma(\alpha_k))} \prod\limits_{k=1}^{n} x_k^{\alpha_k - 1} \times (1 - \sum\limits_{k=1}^{n-1} x_k)^{\alpha_n - 1}, & d = n+1. \end{cases} \tag{10}$$

where $d \in \mathbf{Z}^+$ represents the degree of Dirichlet mapping function and the overall input data dimension is increased by 1 based on equation $\varphi_{n+1}^\alpha(\mathbf{x})$.

4. Case study

4.1. Structural configuration and numerical modeling

In the practical application, an Australian double circuit 500 kV overhead electric transmission tower-line is used to demonstrate the developed framework. The analysis includes three identical transmission towers and each span of 200 m apart. For the middle span, there is a corner connecting two sides of towers, which constructs an angled tower line system for subsequent analyses. For comparison purpose, another all-straight-line system comprising three transmission towers and four straight-line spans located at the same site is also analyzed, as in Figure 6.

Two transmission tower-line system finite element (FE) models for: (i) angled tower line system, and (ii) all-straight-line tower system are developed in ABAQUS 2021, by using beam elements for the tower components and truss elements for the transmission lines. The tower structure was modeled as a frame with beam-column elements to explicitly capture the flexural yielding limit state in individual members and accounts for both axial and bending effects, making it more suitable for evaluating structural response under extreme loading conditions, such as strong winds, and storms. For boundary conditions, all tower structures all fixed to the ground and the two ends of transmission lines are pinned. The main tower structures are defined with elastoplastic properties and the transmission lines are considered as linear elastic.

4.2. Characterization of uncertainties

There are a number of uncertainty sources involved in the fragility analysis of tower-line system subjected to wind excitations, mainly including the applied wind loads, structural geometric dimensions, connections and material properties. Elastic modulus and yield strength are treated as spatial variables and the possible realizations of the random field simulator are 3-D domains that depict various correlation lengths in all three spatial dimensions as shown in Figure 7. From the plots, it is clear that different correlation lengths affect the spatial dependency of structural members material properties. Three different cases are considered: (1) No correlation length (statistically independent), (2) CL1 with [x,y,z] correlation lengths each equal to 5 m and (3) CL2 with [x,y,z] correlation lengths each to 15 m are

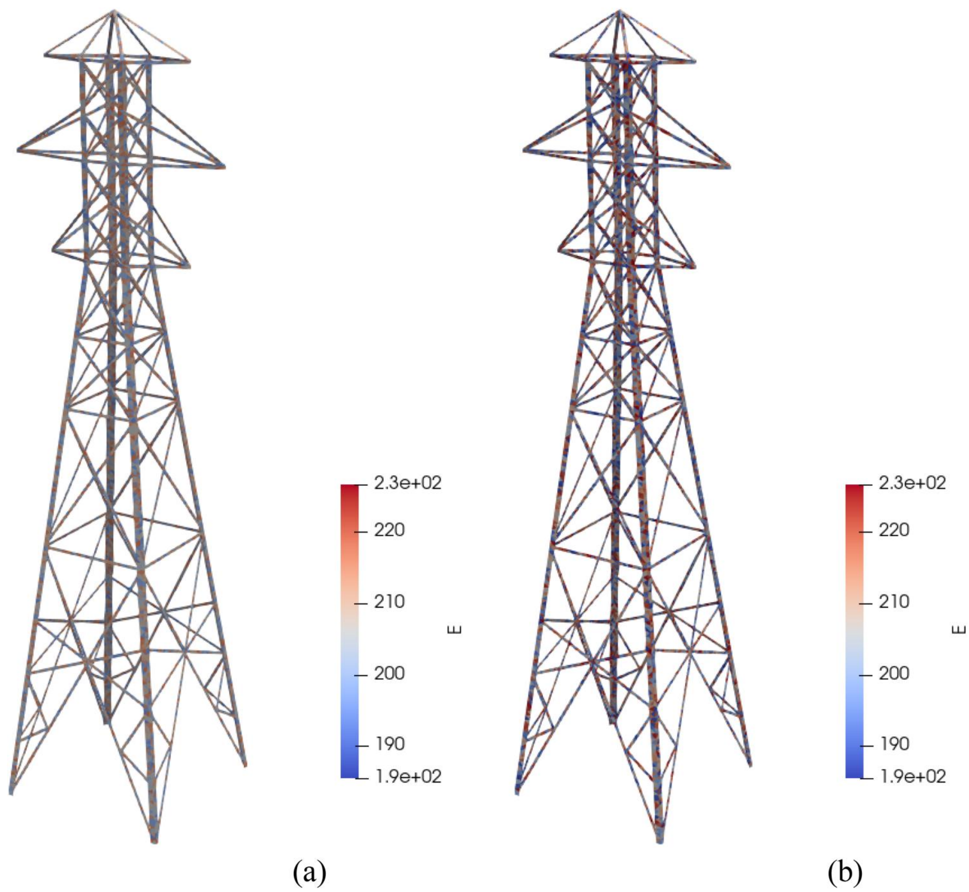


Figure 7. Simulated random field for different correlation lengths: (a) 5 m correlation lengths, (b) 15 m correlation lengths in all three spatial dimensions within transmission tower.

Table 2. Selected uncertain parameters and their distribution for bolted joints (Roman et al., 2024; Ungkurapinan et al., 2003).

	Parameter	Mean	COV	Distribution
Single-leg bolted joint	A(kN)	20.14	0.2189	Normal
	B(kN)	95.92	0.143	Normal
	C(kN)	158.22	0.065	Normal
	P(mm)	1.69	Deterministic	
	O(mm)	1.53	Deterministic	
	R(mm)	2.60	Deterministic	

adopted for Young's modulus and yield strength. In Table 2, statistical properties have been considered for the modified joint slippage model where A, B and C are fully correlated as shown in Figure 8.

Table 3 lists the material property and wind loading probabilistic distributions, with design (nominal) values given by Australian standards (Standards Australia, 2020; Standards Australia/NewZealand, 2021). A factor k_f to account for the variability of fabrication and erection procedure has been considered for both compression and tension performance of structural members.

The limit state function for the system fragility analysis for each wind attack angle is:

$$G(\mathbf{v},\boldsymbol{\theta}) = \max\begin{bmatrix}\delta_{\text{edge tower1}}(\mathbf{v},\boldsymbol{\theta})\\ \delta_{\text{middle tower}}(\mathbf{v},\boldsymbol{\theta})\\ \delta_{\text{edge tower2}}(\mathbf{v},\boldsymbol{\theta})\end{bmatrix} - \delta_{\text{limit}}(\boldsymbol{\theta}),\ \ \boldsymbol{\theta} = \left[0^{\circ},\ 45^{\circ},\ldots,\ 315^{\circ}\right] \tag{11}$$

where $\max[\delta_{xx}(\mathbf{v},\boldsymbol{\theta})]$ is the maximum top displacement of three towers within the tower-line system at any wind speed $\mathbf{v}$ and direction $\boldsymbol{\theta}$. $\delta_{\text{limit}}(\boldsymbol{\theta})$ is the corresponding three damage states threshold of tower structure under different wind attack angles $\boldsymbol{\theta}$ as in Table 1.

To capture the responses of structures for virtual modeling, a uniform distributed 0.2s gust wind speed is generated from 0 to 80 m/s (Collings, 2021), and a total of 1000 wind load samples under each wind attack angle are generated for 1000 uncertain finite element (FE) models as MCS reference results.

4.3. Fragility assessment of all-straight-line system

As mentioned in Section 4.1, three different cases: (1) No correlation length, which makes the uncertainties as statistically independent random variables, (2) CL1 with [x,y,z] correlation length = 5 m and (3) CL2 with [x,y,z] correlation length = 15 m are adopted for Young's modulus and yield strength to illustrate the importance of random field and correlation lengths toward structural fragility. Figure 9 shows the percentage of member and connection failures recorded with different gust wind velocities under wind attack angle of 0°. It's found that, as expected: (i) ignoring the spatial variabilities of material properties underestimates likelihood of damage, (ii) variations of correlation lengths of random fields have an impact upon the overall stochastic structural responses, and typically higher damage likelihood will be generated with the increase of correlation length, (iii) a tower-line system is less vulnerable than a single transmission tower due to its interconnected design, which redistributes loads across multiple towers, enhancing overall structural stability and reducing the likelihood of failure. In such systems, external forces like wind, ice, or other activity are less likely to cause catastrophic failure because the load can transfer to adjacent towers, whereas a single tower bears all forces independently, making it more vulnerable. In all analyses to follow the correlation length is taken as 15 m for Young's modulus and yield strength.

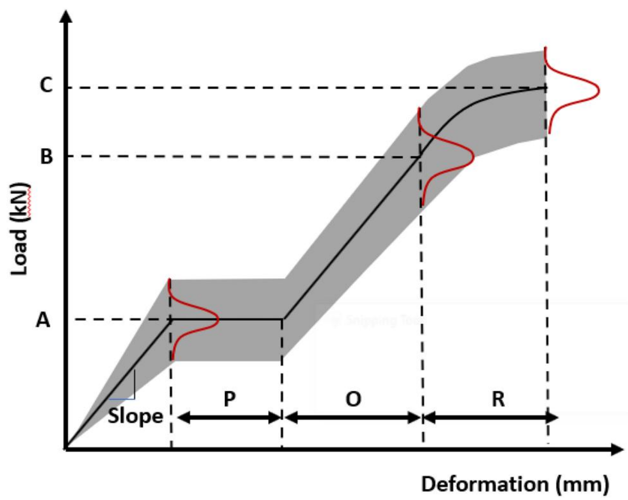


Figure 8. Random modified joint slippage model proposed by Ungkurapinan et al. (2003).

The probabilistic distribution profiles and fragility curves of all-straight-line system under wind attack angle of 0° are plotted in Figure 10. From the plotted results, the established virtual model has high precision and saved 70% of computational costs: (i) MCS (1E3 simulation): 48 h, compared to (ii) Virtual model (300 training samples): 14 h. The exceedance probabilities for damage states at different wind speeds and directions, based on specific return periods (i.e., 50-year return period of 39 m/s, 100-year return period of 42 m/s, and 500-year return period of 45 m/s in Australia), are shown in Table 4. Wind attack angle has a significant

Table 3. Selected uncertain parameters and their spatial/non-spatial distributions.

Parameter			Nominal	Mean-to-nominal	COV	Distribution	References
Spatial uncertainties	Steel Tower	Elastic modulus E(GPa)	200	1.0	0.06	Normal	Stewart (1996)
		Yield strength: $f_{y,C300}$(MPa)	300	1.14	0.06	Normal	Pham et al. (1992)
Non-spatial uncertainties	Conductor	Radius r(mm)	18.3	1.0	0.02	Normal	Salman et al. (2015)
	Fabrication effects	k_f	1.0	1.0	0.10	Normal	(Pham et al., 1992)
	Wind load	Drag force C_d	1.0 (conductor) 1.6 (tower)	1.0	0.05	Lognormal	Pham et al. (1992), Minciarelli et al. (2001)
		Terrain multiplier $M_{z,cat}$	1.0	1.0	0.08	Lognormal	Pham et al. (1992)
		Wind direction multiplier M_d	1.0	0.95	0.02	Lognormal	
		Shielding multiplier M_s	1.0	0.95	0.10	Lognormal	
		Topographic multiplier M_t	1.0	1.0	0.10	Lognormal	

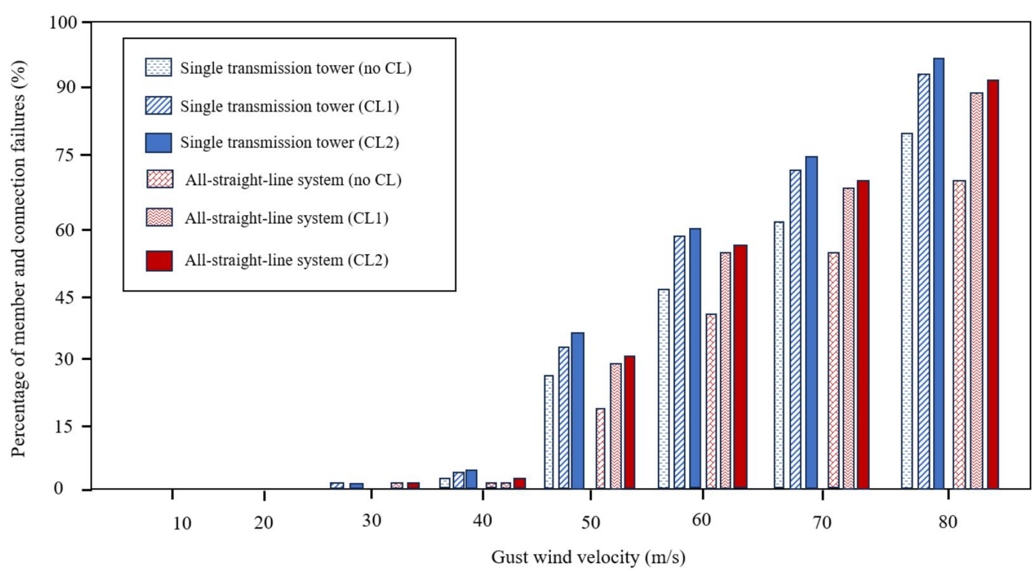


Figure 9. Percentage of member and connection failures for single tower and all-straight-line system for two correlation lengths.

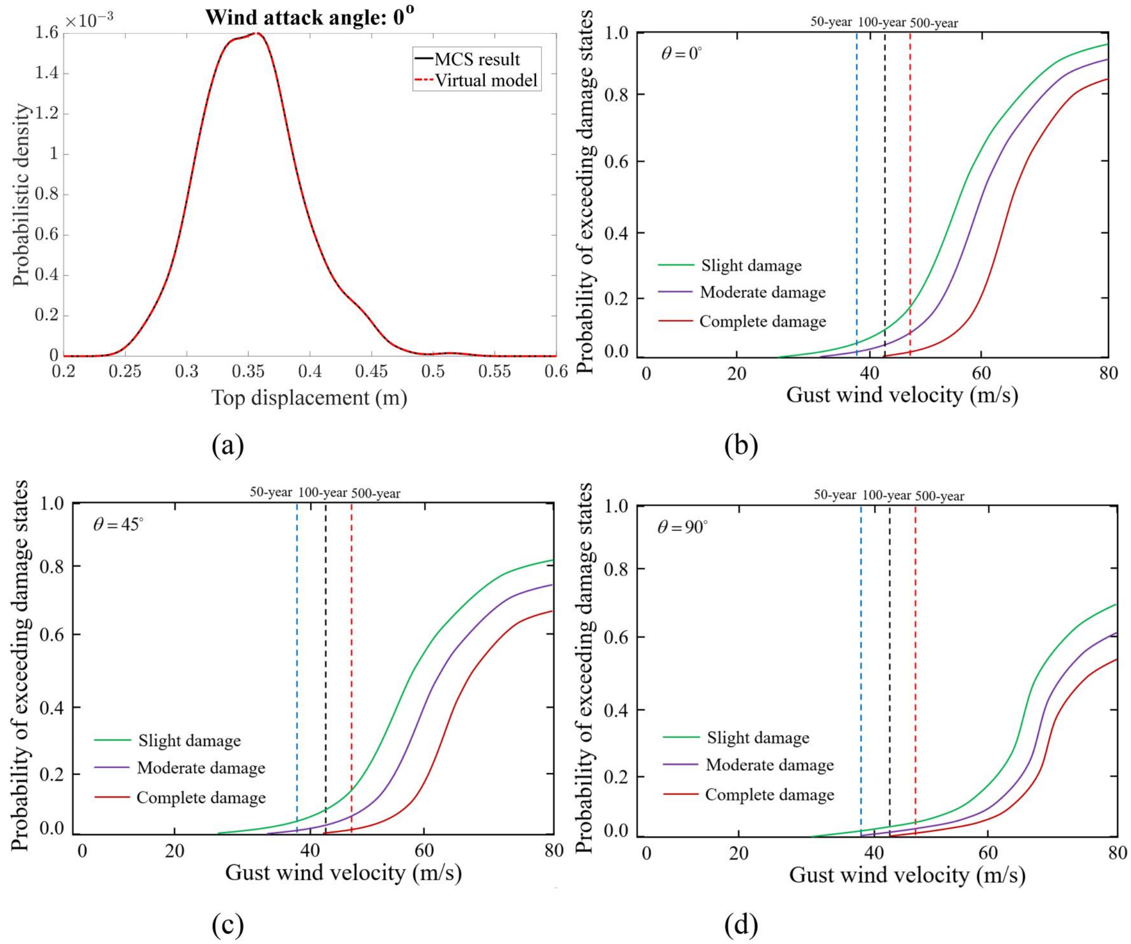


Figure 10. (a) PDF Curves from virtual model and MCS result, (b–d) fragility curves of all-straight-line system under wind angles: 0°, 45°, and 90°.

Table 4. Probability of exceedance for 50, 100, and 500-year return periods of all-straight-line system.

	Slight damage			Moderate damage			Complete damage		
θ	50-year	100-year	500-year	50-year	100-year	500-year	50-year	100-year	500-year
0°	0.053	0.081	0.118	0.021	0.035	0.050	0.0	0.0015	0.0101
45°	0.046	0.060	0.105	0.014	0.025	0.032	0.0	0.0012	0.008
90°	0.019	0.028	0.037	0.005	0.011	0.017	0.0	0.0008	0.006

impact on structural fragility, as indicated by the rightward shift in the curves with increasing wind angles. This is primarily because it directly influences the distribution of aerodynamic forces on a structure, altering how loads are applied to its components. Different wind angles create varying pressure distributions, leading to changes in the magnitude and location of stresses. Structures are typically designed to withstand specific wind directions, and unexpected angles can introduce vulnerabilities, such as asymmetric loading, which may cause twisting, bending, or localized failure.

4.4. Fragility assessment of angled tower-line system

For the angled tower line system, considering the line orientation effect, a total of eight different wind attack angles (i.e., 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) are considered for the fragility analyses. Following the same strategy, individual failure analysis are conducted for both single tower structure and angled tower-line systems, and the peak values of tower top displacements are recorded to assess angled tower-line system's fragility. As in Figure 11, the percentage of member and connection failures recorded for different wind velocities under wind attack angle of 0°. Table 5 shows a comparison of member and connection failure rates for different wind attack angles and speed for single tower, all-straight-line system and angled tower-line system.

Compared to the two types of transmission tower-line systems, the single tower structure exhibits the highest likelihood of failure as demonstrated in Section 4.3. Furthermore, for most wind attack angles, the failure rates of angled tower-line system are slightly higher than that of all-straight-line system. This is because angled system features an angle between the tower structure and lines, which generates lateral tension in the transmission lines. When the wind direction aligns approximately with this angle, the

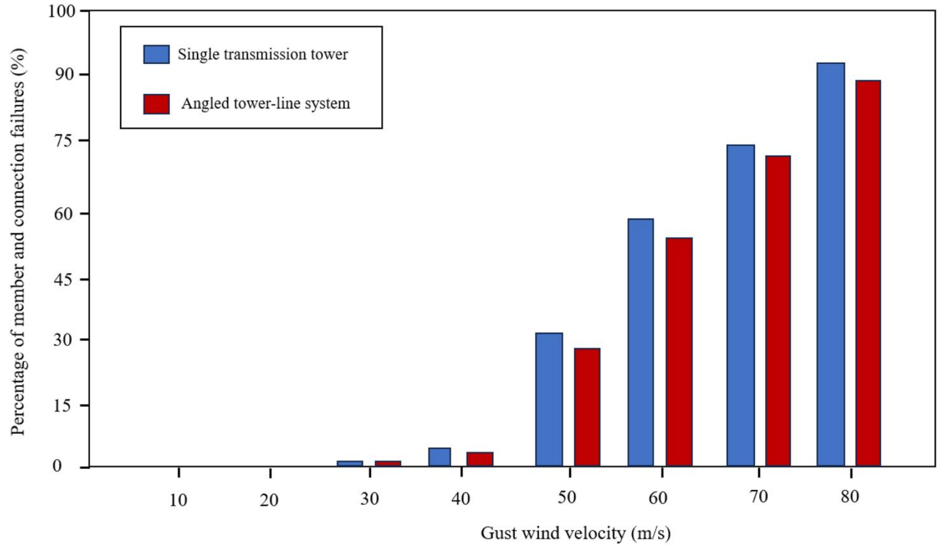


Figure 11. Percentage of member and connection failures for single tower and angled tower-line system.

Table 5. Percentage of member and connection failures for single tower, all-straight-line system and angled tower-line system.

	Single tower			All-straight-line system			Angled tower-line system		
	40m/s	60m/s	80m/s	40m/s	60m/s	80m/s	40m/s	60m/s	80m/s
0°	4.1	54.3	88.5	2.4	46.5	80.2	2.9	50.1	84.6
45°	3.0	45.8	80.1	1.7	36.6	72.1	2.3	40.4	76.3
90°	2.4	42.2	76.5	1.1	33.7	67.4	1.8	36.6	72.5
135°	NA	NA	NA	NA	NA	NA	3.1	52.8	85.1
180°	NA	NA	NA	NA	NA	NA	1.7	35.2	71.3
225°	NA	NA	NA	NA	NA	NA	1.5	32.8	68.7
270°	NA	NA	NA	NA	NA	NA	1.2	30.6	64.9
315°	NA	NA	NA	NA	NA	NA	1.0	28.5	62.1

tension in the lines increases the response of the transmission towers, leading to more components entering a failure state.

The fragility curves and exceedance probabilities for damage states at different wind speeds and directions, based on specific return periods, are once again calculated for angled tower-line system in Figure 12 and Table 6. From the results, the fragility of tower structure under different wind attack cases is varied, and it is shown clearly that the angled tower-line system is vulnerable to wind loads compared to the all-straight-line system. For the all-straight-line system, wind attack angle 0° is the most unfavorable angle while for the angled system, several angles 0°, 45°, 135° are all unfavorable. Thus, more consideration of additional failure mechanisms for an angled tower-line system in practical engineering applications will help tower structures maintain more consistent reliabilities.

4.5. Sensitivity analysis

The sensitivity analysis of tower-line system involves three wind speed of 30 m/s, 50 m/s, and 70 m/s. The main steps include: (1) Prepare the 10th percentile, 50th, and 90th percentile values for each uncertainty parameter (refer to Table 3); (2) Simulate 50 sets of wind load series for each wind load level; (3) Transfer wind speed to 50 FEM-load pairs and calculate each pair to obtain the maximum top displacement for the tower-line system at each wind load level; (4) Repeat this procedure one parameter at a time by setting each parameter to its 10th or 90th percentile value while holding the 50th percentile value of the remaining parameters; (5) Record the variation of each parameter in the sensitivity diagram as in Figure 13.

Figure 13 shows that E, $f_{y,C300}$, k_f, $M_{z,cat}$, M_d, M_s, and M_t have significant influence toward the response of transmission tower-line system and the effects of aerodynamic parameters and material strength on the tower response increase with increasing wind load levels. Among which, the uncertainties of aerodynamic parameters used for wind speed and wind pressure calculations are prominent in the sensitivity analysis and should be investigated thoroughly in the practical wind environment research.

5. Conclusions

A probabilistic wind-induced performance evaluation framework for transmission towers has been developed with the consideration of transmission line orientation. Based on the practical engineering application in Australia, the predicted failure probability of an angled tower-line system, as well as

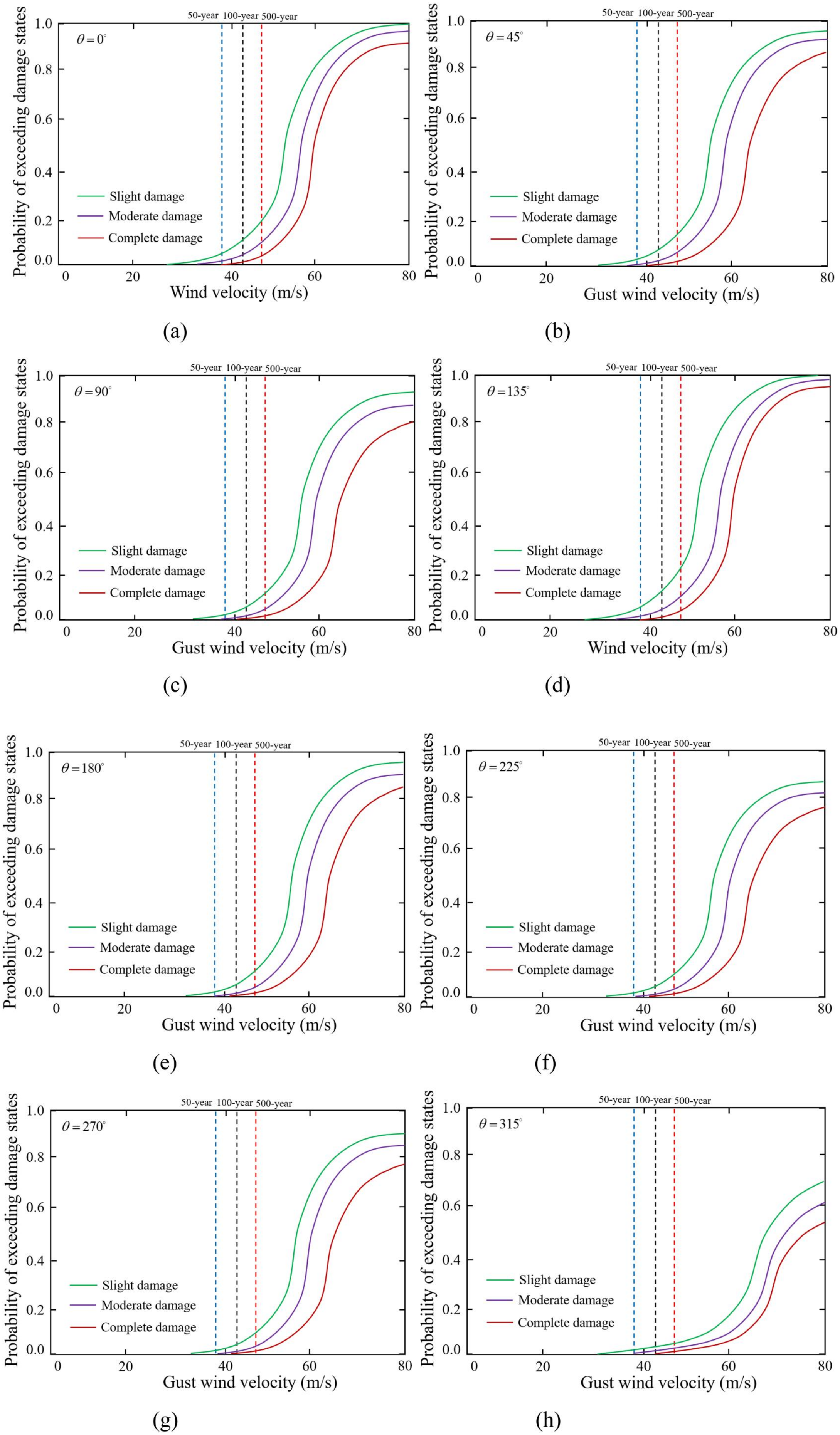


Figure 12. Fragility curves of angled tower-line system under different wind angles.

Table 6. Probability of exceedance for 50, 100, and 500-year return periods of angled tower-line system.

	Slight damage			Moderate damage			Complete damage		
θ	50-year	100-year	500-year	50-year	100-year	500-year	50-year	100-year	500-year
0°	0.061	0.102	0.172	0.019	0.038	0.070	0.001	0.009	0.024
45°	0.035	0.063	0.105	0.007	0.018	0.039	0.0	0.004	0.011
90°	0.025	0.058	0.097	0.005	0.014	0.031	0.0	0.003	0.009
135°	0.073	0.154	0.184	0.025	0.041	0.075	0.002	0.010	0.035
180°	0.023	0.055	0.091	0.003	0.010	0.025	0.0	0.002	0.008
225°	0.021	0.048	0.082	0.002	0.008	0.020	0.0	0.002	0.007
270°	0.019	0.044	0.067	0.002	0.007	0.019	0.0	0.002	0.007
315°	0.016	0.025	0.037	0.001	0.005	0.015	0.0	0.001	0.005

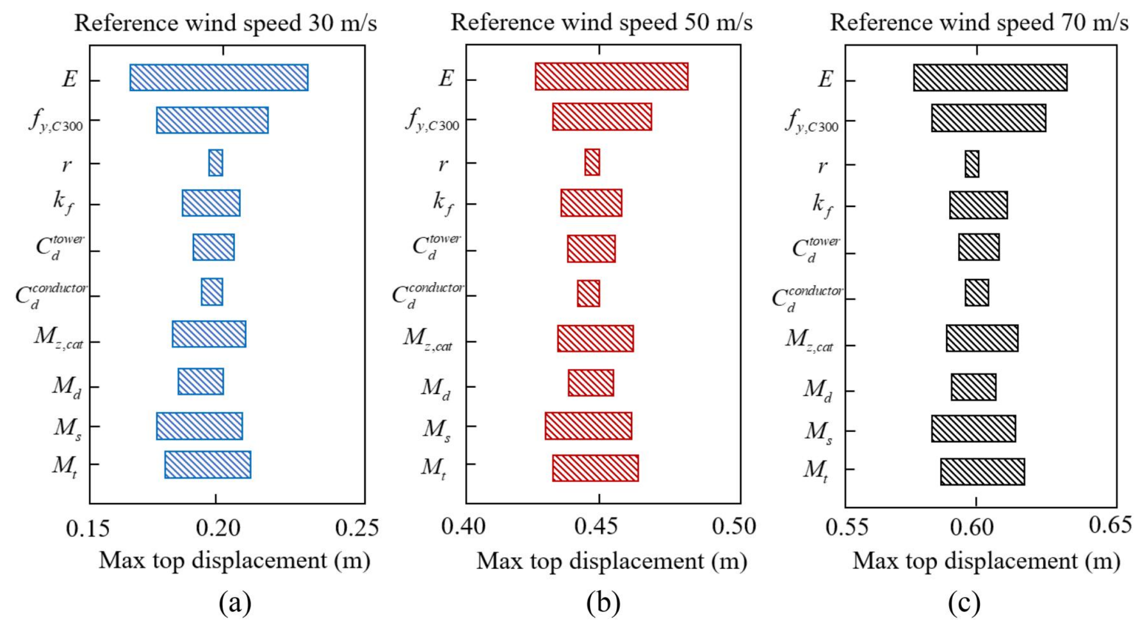


Figure 13. Sensitivity diagrams showing 10th and 90th percentile values of three wind load levels for the tower-line system.

an all-straight tower-line system are calculated. Some conclusions drawn from the simulation results are:

1. A tower-line system is more resistant than a single transmission tower due to its interconnected design, which redistributes loads across multiple towers, enhancing overall structural stability and reducing the likelihood of failure.
2. The angled tower-line system is more vulnerable to wind loads compared to the all-straight-line system. For the all-straight-line system, wind attack angle 0° is the most unfavorable angle while for the angled system, several angles 0°, 45°, 135° are all unfavorable.
3. The structural fragility analysis is approximated by using the surrogate model based on a limited number of training samples, then the predicted fragility curves are verified with the crude MCS results based on a large volume of simulation cycles. Such that the computational efficiency can be improved while maintaining a high calculation accuracy for the surrogate model. In this study, the predicted fragility curves coincide with the MCS results, indicating that the proposed virtual modeling aided fragility analysis technique is accurate and efficient.

The proposed probabilistic approach addresses the random failure behavior of transmission towers, encompassing both material and geometrical nonlinear deformations, with correlated random field factored into the fragility analysis for the first time. Thus, a comprehensive wind fragility framework is developed by incorporating the uncertainties of structural components, wind conditions, and line orientations. Moreover, a novel virtual modeling technique is adopted to simulate the wind-induced fragility model under various wind environment and efficiently assess how these uncertainties affect the tower's capacity and demand, performing accurate predictions to evaluate their impact on fragility outcomes.

The likelihood of complete damage (collapse) of 0.1–2% for the 500-year design wind speed seems to be reasonable and not unexpected. However, the current framework considers three transmission towers, which might be insufficient to represent a complete transmission tower-line system. Relevant work will extend the model to incorporate more towers and evaluate potential variations in system response.

And a detailed risk assessment that couples a stochastic wind field model with a fragility model to fully assess if the damage risks are acceptable and the corresponding strengthening measures such as newly developed composite materials (Tian et al., 2023, 2024) are needed in future research.

For the practical applications of this work, several application scenarios can be considered: (1) The observation that angled tower-line systems are more vulnerable than all-straight tower-line systems suggest that engineers can improve the resistance of tower-line systems by using stronger components or materials at vulnerable angled tower-line locations. (2) Risk-informed decision-making for power grid operators. By using the obtained fragility functions of transmission tower-line systems, the power grid operators can predict the potential probability of failure of tower-line system under extreme wind load conditions, such that prompt decision-making can be assessed to prevent more catastrophic failure events from happening.

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No potential conflict of interest was reported by the author(s).

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