Hindawi
Advances in Civil Engineering
Volume 2022, Article ID 4613323, 12 pages
https://doi.org/10.1155/2022/4613323

Research Article

Reliability Calibration of Tower Members in Transmission Line System Crossing High-Speed Railway

Yunfen Feng,[1] **Shufei Gao**,[1] **and Zeyu Feng**[2]

[1]*School of Architecture and Civil Engineering, Liaocheng University, Liaocheng 252000, Shandong, China*
[2]*Shenxian Yellow River Bureau, Liaocheng 252000, Shandong, China*

Correspondence should be addressed to Yunfen Feng; fengyunfen@lcu.edu.cn

Received 12 May 2022; Revised 10 July 2022; Accepted 1 August 2022; Published 24 August 2022

Academic Editor: John Mander

Due to the rapid development of high-speed railway in China, transmission line systems across the high-speed railway system have become more prevalent in recent years, which highlights the importance of reliable design for systems. The design is generally based on the structural reliability theory, in which the determination of target reliability level is the key. To determine the reliability level of a transmission line across high-speed railway, the statistical parameters of load effects and resistances of tower members are derived and reliability calibration of tower elements satisfying the minimum design requirement in Chinese codes is performed by JC method. Furthermore, the reliability level of a transmission line across high-speed railway is divided into three classes, in which Class 1 is the strongest. According to the calibration results, the minimum target reliability indices are recommended. The results show that the reliability level is similar to the reliability of tower elements in the U.S. but higher than that in Canada. The target reliability indices with values of 3.7, 3.2, and 2.7 are recommended for Class 1, Class 2, and Class 3, respectively.

1. Introduction

With the rapid development of the national economy, the electrical power system has attained prominent achievements in China. The transmission line system, as the electric power carrier, is a lifeline project, which is becoming more and more complex. Therefore, it is necessary to present new requirements for the design philosophy. Meanwhile, the phenomenon of transmission line system crossing the high-speed railway system is increasing substantially with the rapid development of high-speed railway. To ensure the safe operation of high-speed railway, the higher performance requirements for transmission line crossing high-speed railway must be satisfied. Since transmission line systems and rail facilities in China were designed by using different design approaches with various material strengths, partial factors, or safety factors, the safety of transmission system and railway facility cannot be clearly identified only based on the design specifications or codes. For this reason, the identical criterion should be employed to determine the safety of high-speed railway and transmission line system.

During the past 40 years, rapid and significant development has arisen in the field of structural safety. The primary theme in structural safety is reliability analysis, which can be defined as the consistent evaluation of structure safety using probability theory [1]. The uncertainties associated with load effects, material properties, physical dimension, and calculation model are fully taken into account in reliability analysis. Reliability analysis in the industries of buildings, bridges have been extensively carried out, and target reliability indices have been calibrated in the aforementioned industries. However, very little research effort has been conducted on reliability of transmission line system [2–5].

As is known to all, reliability-based design method has been introduced to design standards or codes of electric system in many countries and applied to the design of overhead transmission line, such as "National Electric Safety Code (NESC C2-2002)" [6], "Guidelines for Electrical Transmission Line Structural Loading (ASCE 74–2009)" [7], "Canadian Electrical Code: Overhead Systems (CSA C22.3 No.1–2001)" [8], "Overhead Electrical Lines Exceeding AC

45 kV (EN 50341–1)" [9], and "Design Criteria of Overhead Transmission Lines (IEC 60826–2003)" [10]. The probability-based design method has also been applied to Chinese design codes of overhead transmission line, such as "Technical Regulation of Design for Tower and Pole Structures for Overhead Transmission Line (DL 5154–2012)" [11], "Code for Design of 110 kV~750 kV Overhead Transmission Line (GB 50545–2010)" [12], and "Code for Designing of ±800 kV DC Overhead Transmission Line (GB 50790–2013)" [13]. In the field of rail engineering, reliability-based limit state design method is specified in Chinese standard "Unified Standard for Reliability Design of Railway Structures (GB 50216–2019)" [14].

For ultra-high voltage (UHV) transmission line, in order to satisfy the safety requirement of transmission line across high-speed railway, target reliability indices of the components of transmission line satisfying the minimum requirements should be calibrated. The research is limited to calibration of reliability index and definition of reliability level of transmission tower for transmission line crossing high-speed railway.

2. Statistical Parameters of Load Effects and Resistance

The transmission line is composed of power transmission towers, insulators, fittings, conductors, and Earth wires. To serve its purpose, transmission line system must be safe against various loads, such as the weight of structure itself, wind load, and ice load. In the reliability analysis and design of overhead line structures, probabilistic distributions and statistical parameters of structural load effects and resistance capacity must be determined first.

2.1. Statistical Parameters of Load Effect. Load effects are the moments, shears, and axial forces resulting from the loads on the structure. Statistical distributions of load effects are consistent with that of the loads. Statistical parameters of the loads are defined in terms of the bias factor (the ratio of mean value to nominal value) and coefficient of variation (the ratio of standard deviation to the mean value, abbreviated as COV). It should be pointed out that loads are classified by their characteristics varying with time, that is, permanent load and variable loads such as wind load or ice load.

2.1.1. Permanent Load. The major part of permanent load is the weight of towers, insulators, and fittings. Based on the existing researches, permanent load follows a normal distribution [15]. Based on the results of statistical analysis of building structure, the bias factor of permanent load $k_G = 1.06$ and COV $\delta_G = 0.07$ are suggested in the article [15].

2.1.2. Wind Load. Wind load is one of the major variable loads acting on overhead transmission line. The action mechanism of wind load on overhead transmission line is very complicated. The same statistical parameters and probability distribution as that used in building structures are employed in this work. Wind load normally follows a Gumbel distribution. Two load cases will be considered as described below.

(1) The Extreme Wind Load Case. 30 m/s was taken as reference wind speed in the extreme wind load case and the speed can be treated as standardized wind speed which is used to define the standard value of wind pressure W_k in Chinese code. The bias factor and COV of the extreme wind load are taken as $k_{WT} = 0.908$ and $\delta_{WT} = 0.193$, referencing the statistical parameters of building structure designed using Chinese codes [16].

(2) The Combined Wind and Ice Load Case. 10 m/s is taken as the reference wind speed in the combined wind and ice load case. It is assumed that the wind speed of 10 m/s is the maximum wind speed for the condition of annual maximum ice thickness, so the average wind load effect can be estimated by the following equation:

$$\begin{aligned}\mu_{wt} &= \mu_{WT} + \frac{\ln(t/T)}{\alpha_{WT}} = \mu_{WT} + \frac{\sigma_{WT}\ln(t/T)}{1.2826} \\ &= 0.908W_k + \frac{0.1752W_k \times \ln(1/12/50)}{1.2826} \\ &= 0.034W_k,\end{aligned} \tag{1}$$

where μ_{wt} is the mean of wind load for the combined wind and ice load case; μ_{WT} and σ_{WT} are the mean and standard deviation of wind load in the extreme wind load case, respectively; α_{WT} is the scale parameter of Gumbel distribution, taken as 1.2826; t is 1 month; and T is the return period of wind load, taken as 50 years.

Hence, the bias factor of wind load equals 0.034 for the combined wind and ice load case. The COV of wind load is still assumed to be taken as 0.193.

2.1.3. Ice Load. When drops of water in the air and wet snow are in contact with components of overhead transmission line, such as conductors, insulators, and fittings, the coagulated ice on power transmission conductors may occur. There are many natural factors affecting icing, such as weather, terrain, altitude, wind speed and direction, and cable conductor.

Given that the icing thickness is not even, substantial uncertainties cannot be neglected in this problem. Ideally, the statistics of ice thickness used for reliability analysis should be obtained from the local weather stations. However, due to the lack of statistical data available related to the coagulated ice, the statistical results of observation station in Enshi of Hubei Province are used in the article [17]. Based on the previous statistical data [17] and engineering experience, ice load is assumed to follow a lognormal distribution with the bias factor $k_I = 1.1$ and the COV $\delta_I = 0.3$.

2.2. Statistical Parameters of Resistance. Resistance is the ability of components and structures to resist load effects. There is indeed a high degree of uncertainty associated with structural resistance, mainly from three aspects: the uncertainties in material properties, the uncertainties associated with geometric dimensioning, and calculation model.

2.2.1. Strength Calculation of Axially Loaded Members. According to Chinese code "DL/T 5154–2012" [11], the resistance for strength calculation of axially loaded tower members can be expressed as

$$R = \Omega_{\mathrm{P}} m A f, \tag{2}$$

where Ω_{P} is the model error of Equation (2), m is the strength reduction factor; A is the cross-sectional area of tower members; and f is the material strength of tower members.

The bias factor and COV can be, respectively, described by the following relationships:

$$k_{\mathrm{R}} = \frac{\mu_{\mathrm{R}}}{R_{\mathrm{k}}} = k_P \frac{m\mu_{\mathrm{A}}\mu_{\mathrm{f}}}{A_{\mathrm{k}} f_{\mathrm{k}}} = k_P m k_A k_f, \tag{3}$$

$$\delta_R = \sqrt{\delta_P^2 + \delta_A^2 + \delta_f^2}, \tag{4}$$

in which k_{P}, k_{A}, and k_{f} as well as δ_{P}, δ_{A}, and δ_{f} denote, respectively, the bias factor and COV of the calculation model, cross-sectional area, and material strength of tower members, as shown in Table 1 [18]; f_{k}, A_{k}, and R_{k} are the characteristic value of steel strength, cross-sectional area of tower members, and resistance, respectively.

Substitution of the parameters in Table 1 into (3) and (4) can estimate the statistical parameters of resistance for strength calculation of axially loaded members of tower, namely, $k_{\mathrm{R}} = 1.134$ and $\delta_{\mathrm{R}} = 0.117$.

2.2.2. Stability Calculation of Axial Compression Members. Similarly, based on DL/T 5154–2012, the resistance for stability calculation of axial compression members of tower can be written as

$$R = \Omega_{\mathrm{P}} \phi m_{\mathrm{N}} A f, \tag{5}$$

where ϕ is the stability coefficient of axial compression tower member and m_{N} is the stability reduction factor of compression chord member.

Therefore, the bias factor and COV of resistance can be, respectively, computed by

$$k_R = \frac{\mu_R}{R_k} = \frac{\mu_{\Omega_p}\mu_A\mu_\phi m_N \mu_f}{A\phi_k m_N f_k} = k_P k_\phi k_A k_f, \tag{6}$$

$$\delta_R = \sqrt{\delta_P^2 + \delta_\phi^2 + \delta_A^2 + \delta_f^2}, \tag{7}$$

where k_ϕ and δ_ϕ are the bias factor and COV of ϕ. Statistical parameters of Ω_{P} in (6) and (7) are listed in Table 2 [18]. Statistical parameters of ϕ shown in Table 2 are derived by the following method.

According to Chinese code DL/T5154-2012 [11], ϕ can be calculated as

$$\phi = \begin{cases} 1 - \alpha_1 \overline{\lambda}^2 & \overline{\lambda} \le 0.215 \\ \dfrac{1}{2\overline{\lambda}^2}\left[\left(\alpha_2 + \alpha_3\overline{\lambda} + \overline{\lambda}^2\right) - \sqrt{\left(\alpha_2 + \alpha_3\overline{\lambda} + \overline{\lambda}^2\right)^2 - 4\overline{\lambda}^2}\right] & \overline{\lambda} > 0.215 \end{cases}, \tag{8}$$

in which $\overline{\lambda}$ is defined as

$$\overline{\lambda} = \frac{\lambda}{\pi}\sqrt{\frac{f_{\mathrm{y}}}{E}}, \tag{9}$$

where λ is slenderness ratio of tower member; f_{y} is steel yield strength; E is elastic modulus of steel; and α_1, α_2, and α_3 are factors specified in Chinese code DL/T 5154–2012 [11].

Since the stability coefficient ϕ shown in (8) is a piecewise function, the definition of probability distribution function and statistical parameters of ϕ are complicated. In order to determine the statistical parameters of the stability coefficient ϕ, steel yield strength f_{y} is considered as random variable following a normal distribution with a bias factor of 1.08 and a COV of 0.08 [18]. Generally speaking, the variability of elastic modulus E is very small and a constant value of 2×10^5 MPa is adopted in the article.

Then, 100,000 random numbers for f_{y} is achieved through Monte Carlo simulation (MCS), which are substituted into (8), thereby obtaining the random values of ϕ. According to the aforementioned statistical analysis, the statistical parameters of ϕ for λ of 10, 50, and 100 are given in Table 3, in which Section a and Section b are classifications of a cross-section of members in Chinese code DL/T 5154–2012 [11]. The readers are referred to [11] for detailed information about the classification of section and steel classes (i.e. Q235 and Q345). For illustrative purposes, slenderness ratio $\lambda = 50$ of Section b is taken as an example, and the frequency histogram of ϕ/ϕ_{k} is depicted in Figure 1, where ϕ_{k} is the characteristic value of ϕ. The bias factor of ϕ is equal to 1.025, COV of ϕ is equal to 0.068, as listed in Table 3.

Table 1: Statistical parameters of resistance for strength calculation of axially loaded members.

Variables	Statistical parameters	
	k	δ
Ω_{P}	1.05	0.07
A	1.00	0.05
f	1.08	0.08

Table 2: Statistical parameters of resistance for stability calculation of axial compression members.

Variables	Statistical parameters	
	k	δ
Ω_{P}	1.070	0.096
ϕ	1.025	0.068

Table 3: Bias factor and COV of ϕ/ϕ_k.

Section type	λ	Q235				Q345			
		Steel thickness $d > 16 \sim 40$ mm		Steel thickness $d > 40 \sim 60$ mm		Steel thickness $d > 16 \sim 35$ mm		Steel thickness $d > 35 \sim 50$ mm	
		Bias factor	COV	Bias factor	COV	Bias factor	COV	Bias factor	COV
Section a	10	1.090	0.000	1.088	0.000	1.109	0.001	1.104	0.001
	50	0.994	0.007	0.994	0.007	0.990	0.011	0.991	0.010
	100	0.954	0.051	0.956	0.049	0.944	0.068	0.946	0.062
Section b	10	1.152	0.001	1.148	0.001	1.186	0.001	1.177	0.001
	50	0.990	0.011	0.990	0.011	0.984	0.017	0.986	0.015
	100	0.957	0.049	0.958	0.048	0.948	0.060	0.950	0.058
Average value		1.023	—	1.022	—	1.027	—	1.026	—
Grand average					1.025				

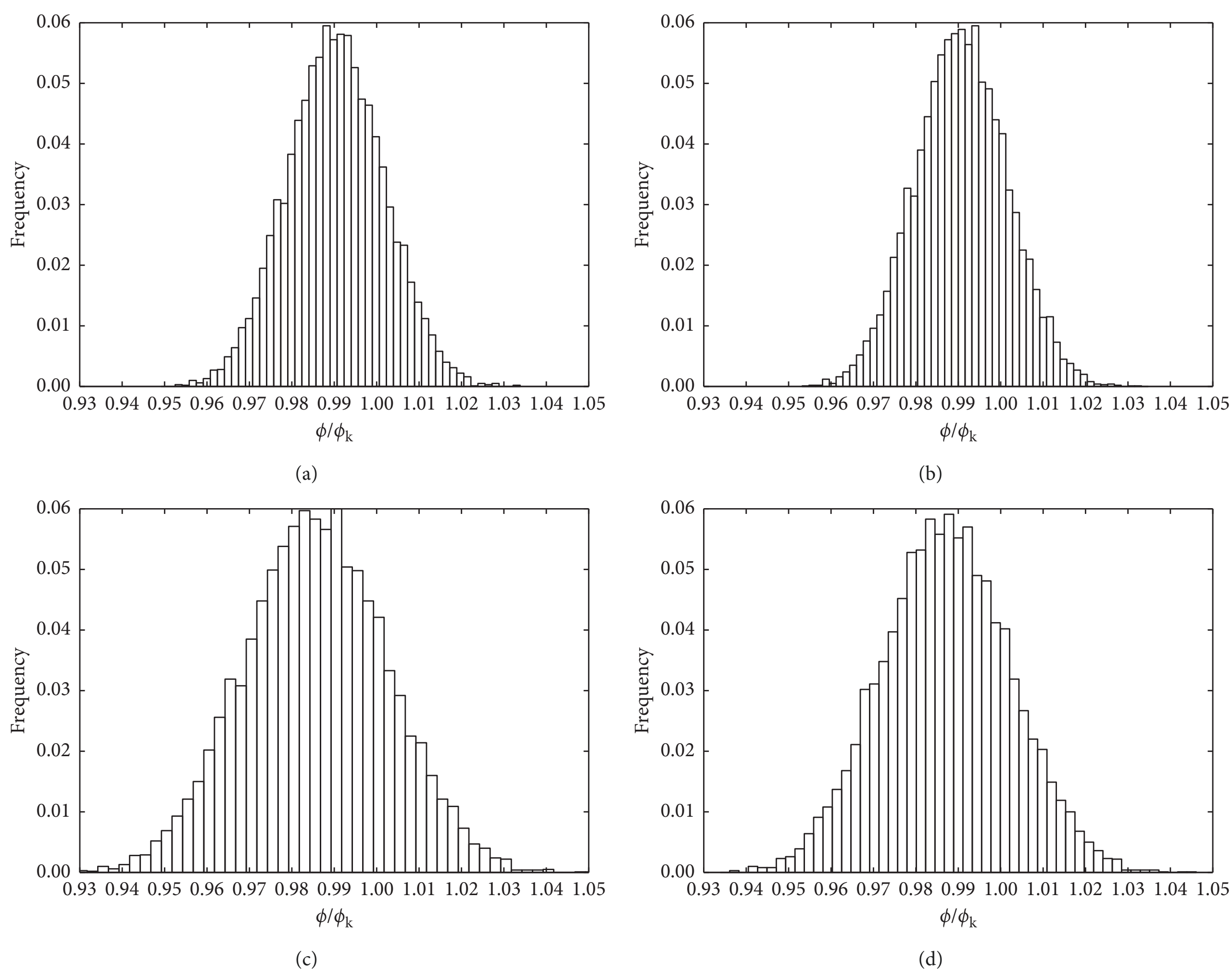

Figure 1: Frequency histogram of ϕ/ϕ_k for slenderness ratio $\lambda = 50$ of Section b. (a) Q235: $d > 16$~40 mm, (b) Q235: $d > 40$~60 mm, (c) Q345: $d > 16$~35 mm, and (d) Q345: $d > 35$~50 mm.

Consequently, substituting statistical parameters of all random variables shown in (6) and (7) can obtain that the bias factor and COV of resistance for stability calculation of axial compression members are 1.185 and 0.150, respectively.

2.3. Summary of Statistical Parameters for Load Effects and Resistance. A summary of the statistical parameters is given in Table 4 including bias factor, COV, and distribution type.

Table 4: Statistical parameters of load effect and resistance of transmission tower.

Variables			Statistical parameters k	Statistical parameters δ	Probability distribution
Load effect		Permanent load	1.060	0.070	Normal distribution
	Wind load	Extreme wind load case	0.908	0.193	Gumbel distribution
		Wind + ice load	0.034	0.193	
		Ice load	1.100	0.300	
Resistance		Strength calculation	1.134	0.117	Lognormal distribution
		Stability calculation	1.185	0.150	

3. Reliability Calibration

3.1. Primary Expressions in Chinese Design Codes. The reliability indices for structures or components designed according to Chinese codes representing the minimum design requirements can be determined by calibration of reliability. Based on Chinese codes "DLT5154-2012" [11] and "GB 50545–2010" [12], design expression with partial safety factor for ultimate limit state is written as

$$\gamma_0\left(\gamma_G S_{Gk}\&9; +\psi \sum \gamma_{Q_i} S_{Q_i k}\right) \le R_d, \tag{10}$$

where γ_0 is the coefficient for importance of structure, not less than 1.1 for the important transmission line, 0.9 for the temporary transmission line, 1.0 for the other transmission line;γG is the partial safety factor of permanent load, not more than 1.1 in favorable conditions, 1.2 in unfavorable conditions; γ_{Qi} is the partial safety factor of variable load Q_i taken as 1.4; S_{Gk}, $S_{\mathrm{Q}ik}$ are, respectively, characteristic value of permanent load effect and variable load effect; R_{d} is design value of components or structures, and different formulas are adopted for different tower members in Chinese code GB 50545–2010 [12]; Ψ is combination coefficient of variable load, 1.0 for normal operation condition, 0.9 for the design condition of conductor breaking, installation, and uneven icing, and 0.75 for checking calculation.

According to (10), the design value of resistance satisfying the minimum design requirements specified by Chinese codes can be expressed by

$$R_d = \gamma_0\left(\gamma_G S_{Gk} + \psi \sum \gamma_{Q_i} S_{Q_i k}\right). \tag{11}$$

3.2. Determination of Reliability Index

3.2.1. Expression of Resistance

(1) Strength Calculation of Axially Loaded Members. The strength of tower member in axial stress given by Chinese codes is written as [11]

$$\frac{N}{A_{\mathrm{n}}} \le m f_{\mathrm{d}}, \tag{12}$$

where A_{n} is the net cross-sectional area of tower member and f_{d} is the design value of steel strength.

The axial force should meet the minimum design requirements described by (12) and can be expressed as follows:

$$N = R_d = m A_n f_d. \tag{13}$$

Substitution of (13) into (11) leads to

$$\gamma_0\left(\gamma_G N_{Gk} + \psi \sum \gamma_{Q_i} N_{Q_i k}\right) = m A_n f_d, \tag{14}$$

in which N_{Gk} and N_{Qik} are, respectively, the characteristic value of permanent load and variable loads.

(2) Stability Calculation of Axial Compression Members. Correspondingly, the stability calculation of axial compression member should satisfy the following expression given by Chinese code "DL/T 5154–2012" [11]:

$$\frac{N}{\phi_k A_n} \le m_N f_d, \tag{15}$$

where ϕ_{k} is the characteristic value of stability coefficient ϕ for stability calculation of tower member in axial compression.

Then, Equation (11) can be rewritten by the following formula:

$$\gamma_0\left(\gamma_G N_{Gk} + \psi \sum \gamma_{Q_i} N_{Q_i k}\right) = \phi_k m_N A_n f_d. \tag{16}$$

3.2.2. Calculation of Reliability Index. The variable loads of transmission tower include wind, ice, conductor, or ground wire broken loads, but for the sake of simplicity, only the extreme wind load case and the combined wind and ice load case are considered in this work. As shown in Table 4, in addition to the statistical parameters of resistance, the function and statistical parameters of load effects are taken as the same values for both strength and stability calculation of axially loaded tower members. Therefore, for illustrative purpose, calculation of reliability index for strength calculation of axially loaded tower members is taken as example.

(1) Extreme Wind Load Case. The performance function of transmission tower for strength calculation of axially loaded member can be expressed as follows:

$$Z = R - N_{\mathrm{G}} - N_{\mathrm{W}}, \tag{17}$$

where R is the resistance; N_{G} is the axial force resulting from permanent load acting on tower member; and N_{W} is the axial force resulting from the extreme wind load acting on tower member.

Table 5: Characteristic values and design values of steel strength.

Steel thickness (mm)	Q235		Q345	
	f_k (MPa)	f_d (MPa)	f_k (MPa)	f_d (MPa)
$d \le 16$	235	215	345	310
$d > 16 \sim 40$	235	205	345	295
$d > 40 \sim 60$	235	200	345	265
$d > 60 \sim 100$	235	190	345	250

The mean and standard deviation of permanent load and wind load can be expressed as follows:

$$\mu_{N_G} = k_{N_G} N_{Gk}, \sigma_{N_G} = \delta_{N_G} k_{N_G} N_{Gk}, \tag{18}$$

$$\mu_{N_W} = k_{N_W} \rho_W N_{Gk}, \sigma_{N_W} = \delta_{N_W} k_{N_W} \rho_W N_{Gk}, \tag{19}$$

where k_{N_G}, k_{N_W}, δ_{N_G}, and δ_{N_W} are the bias factors and COV of permanent load and wind load, respectively; ρ_W is the wind load effect ratio, which is the ratio of the characteristic value of wind load to the characteristic value of permanent load and can be expressed as $\rho_W = N_{Wk}/N_{Gk}$.

The mean of resistance can be expressed as follows:

$$\mu_R = k_R R_k = k_R (m A_n f_d) \frac{f_k}{f_d}. \tag{20}$$

The characteristic value f_k and the design value f_d of steel strength for various steel classes and thicknesses are summarized in Table 5.

Wind loads on power transmission tower include the wind loads acting on the tower members as well as conductors, overhead ground wires, insulators, and fittings. When determining wind loads acting on conductors and ground wires designed by Chinese code "GB50545-2010," wind load adjustment factor β_c shown in Table 6 should be taken into account. Experience shows that wind loads acting on conductors, overhead ground wires, insulators, and fittings can be taken half of the total wind loads on tower. Therefore, by substituting (14) into (20), the following equations can be obtained:

$$\begin{aligned}\mu_R &= k_R \frac{f_k}{f_d} \left[\gamma_G N_{Gk} + 0.5 (1 + \beta_c) \gamma_{Q_1} N_{Wk}\right] \\ &= k_R \frac{f_k}{f_d} \left[\gamma_G + 0.5 (1 + \beta_c) \gamma_{Q_1} \rho_W\right] N_{Gk}.\end{aligned} \tag{21}$$

As seen in (18), (19), and (21), the mean and standard deviation of structure resistance, permanent load effect, and wind load effect are proportional to the characteristic value of permanent load N_{Gk}. It is well known that the value of reliability index depends on the wind load effect ratio ρ_W rather than the specific value of load effects and resistance. Analyses of numerous actual power transmission towers have shown that the ratio ρ_W tends to lie within a wider range of values ranging from 0.1 to 100.

The most widely used approach for reliability analysis is JC method. Then reliability indices β of tower members for various steel classes with different wind load adjustment factors β_c are calculated according to JC method in this work, as shown in Figures 2 and 3. The average values of reliability indices of various steel classes for different wind load adjustment factors β_c are summarized in Table 7.

Table 6: Wind load adjustment coefficient β_c.

Wind speed (m/s)	<20	20 ~ 27	27 ~ 31.5	≥31.5
βc	1.0	1.1	1.2	1.3

It can be seen from Figures 2 and 3 that the reliability indices of power transmission tower members relate directly to the ratio ρ_W. For $\rho_W \le 1.0$, the reliability indices for strength calculation of axially loaded tower members increase with the increased ρ_W; meanwhile, for $\rho_W > 1.0$, the reliability indices decrease with the increased ρ_W. As shown in Table 7, the average values of reliability indices increase with the wind load adjustment factor β_c, while the average values of reliability indices for stability calculation of axial compression members are always lower than those for strength calculation.

(2) The Combined Wind and Ice Load Case. Axially loaded tower members in strength calculation are still taken as examples herein. In the combined wind and ice load case, the performance function of transmission tower member for strength calculation of axially loaded member can be expressed as follows:

$$Z = R - N_G - N_W - N_1. \tag{22}$$

So, the mean values and standard deviations of wind load and ice load in the combined wind and ice load case are written as follows:

$$\begin{aligned}\mu_{N_{WI}} &= k_{N_{WI}} \rho_{W_I} N_{Gk}, \sigma_{N_{WI}} = \delta_{N_{WI}} k_{N_{WI}} \rho_{W_I} N_{Gk}, \mu_{N_I} \\ &= k_{N_I} \rho_I N_{Gk}, \sigma_{N_I} = \delta_{N_I} k_{N_I} \rho_I N_{Gk},\end{aligned} \tag{23}$$

where $k_{N_{WI}}$,k_{N_I}, $\delta_{N_{WI}}$, and δ_{N_I} are, respectively, the bias factors and COV of wind load and ice load in the combined wind and ice load case; ρ_{W_I} is the wind load effect ratio, $\rho_{W_I} = N_{Wk}/N_{Gk}$; ρ_I is the ice load effect ratio,$\rho_I = N_{Ik}/N_{Gk}$.

According to Table 6, β_c for the combined wind and ice load case is equal to 1, since the wind speed of 10 m/s is assumed to be the maximum wind speed for the condition of annual maximum ice thickness. Therefore, the mean of resistance for stability calculation of axial compression member is defined as:

$$\mu_R = k_R \frac{f_k}{f_d} \left[\gamma_G + \gamma_{Q_1} \rho_{W_I} + \gamma_{Q_2} \rho_I\right] N_{Gk}, \tag{24}$$

where γ_{Q_2} is the partial factor of ice load.

For the combined wind and ice load case, ice loads would dominate the reliability of tower. In accordance with the analysis results of actual power transmission towers, the ratio ρ_{W_I} tends to lie within the range 0.02~10, while ρ_I ranges from 0.02 to 5.

To compute the reliability indices of tower members in the combined wind and ice load case, JC method is employed in the present article. The reliability indices for different ρ_{W_I} and ρ_I are depicted in Figures 4 and 5; meanwhile, the average values of reliability indices for various steel classes are shown in Table 8.

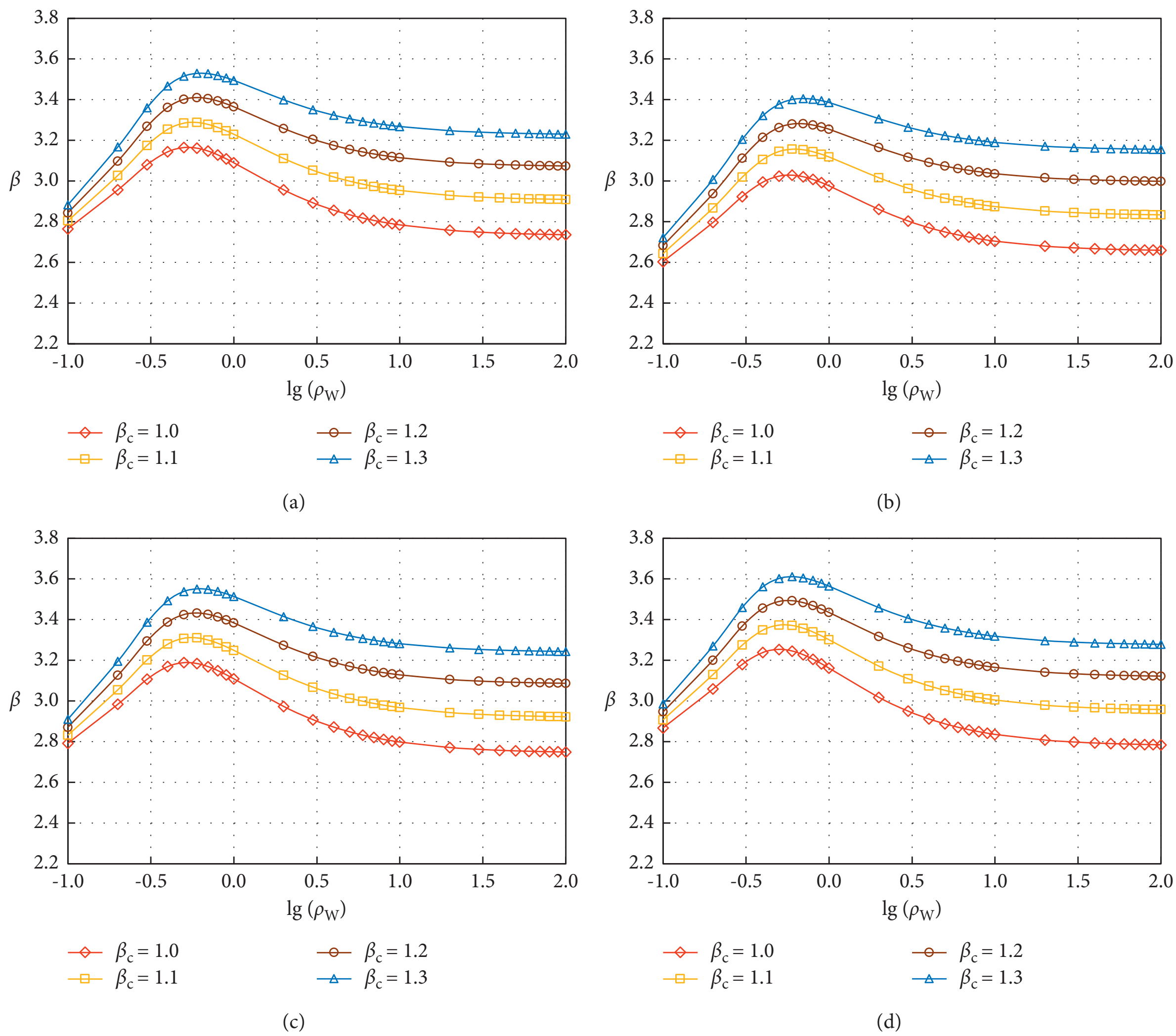

FIGURE 2: Reliability indices for strength calculation of axially loaded member. (a) Q235: $d > 16{\sim}40$ mm, (b) Q235: $d > 40{\sim}60$ mm, (c) Q345: $d > 16{\sim}35$ mm, and (d) Q345: $d > 35{\sim}50$ mm.

As can be seen in Figures 4 and 5, when the ice load effect ratio ρ_{I} is taken a fixed value, the reliability indices increase with the ratio $\rho_{\mathrm{W_I}}$, while the reliability indices decrease with ρ_{I} in the case of a fixed wind load effect ratio $\rho_{\mathrm{W_I}}$. Since the reliability in the combined wind and ice load case is governed mainly by ρ_{I}, a higher reliability level is produced for $\rho_{\mathrm{W_I}} > 0.1$ and $\rho_{\mathrm{I}} < 0.1$, as compared with the extreme wind load case. However, the average reliability indices of axial compression member under stability are lower than those of axially loaded member for strength calculation, as shown in Table 8.

4. Target Reliability Index of Transmission Tower for Transmission Line System Crossing High-Speed Railway

4.1. Reference Value of Reliability Index β_0. The reliability analysis is carried out for transmission tower designed by Chinese codes "GB 50545–2010" and "DL/T 5154–2012," and average values of the above-mentioned reliability indices shown in Tables 7 and 8 are listed in Table 9.

It can be seen from Table 9 that the average values of reliability indices for strength calculation of axially loaded member are 3.1028 in the extreme wind load case and 3.3479 in the combined wind and ice load case, respectively. The average reliability indices for stability of axial compression member are, respectively, 2.9949 in the extreme wind load case and 3.1983 in the combined wind and ice load case. Based on the analysis and adjustment of the average reliability indices, the reference value of reliability index of transmission tower is presented for transmission line employing 50-year design reference period and crossing high-speed railway in this work, as shown in Table 10. The reference value shown in Table 10 represents the reliability level of transmission tower meeting the minimum design requirements specified by "GB 50545–2010" and "DL/T 5154–2012."

4.2. Target Reliability Index β_T

4.2.1. Safety Classes. In general, it is difficult to quantificationally calculate the loss due to structural failure.

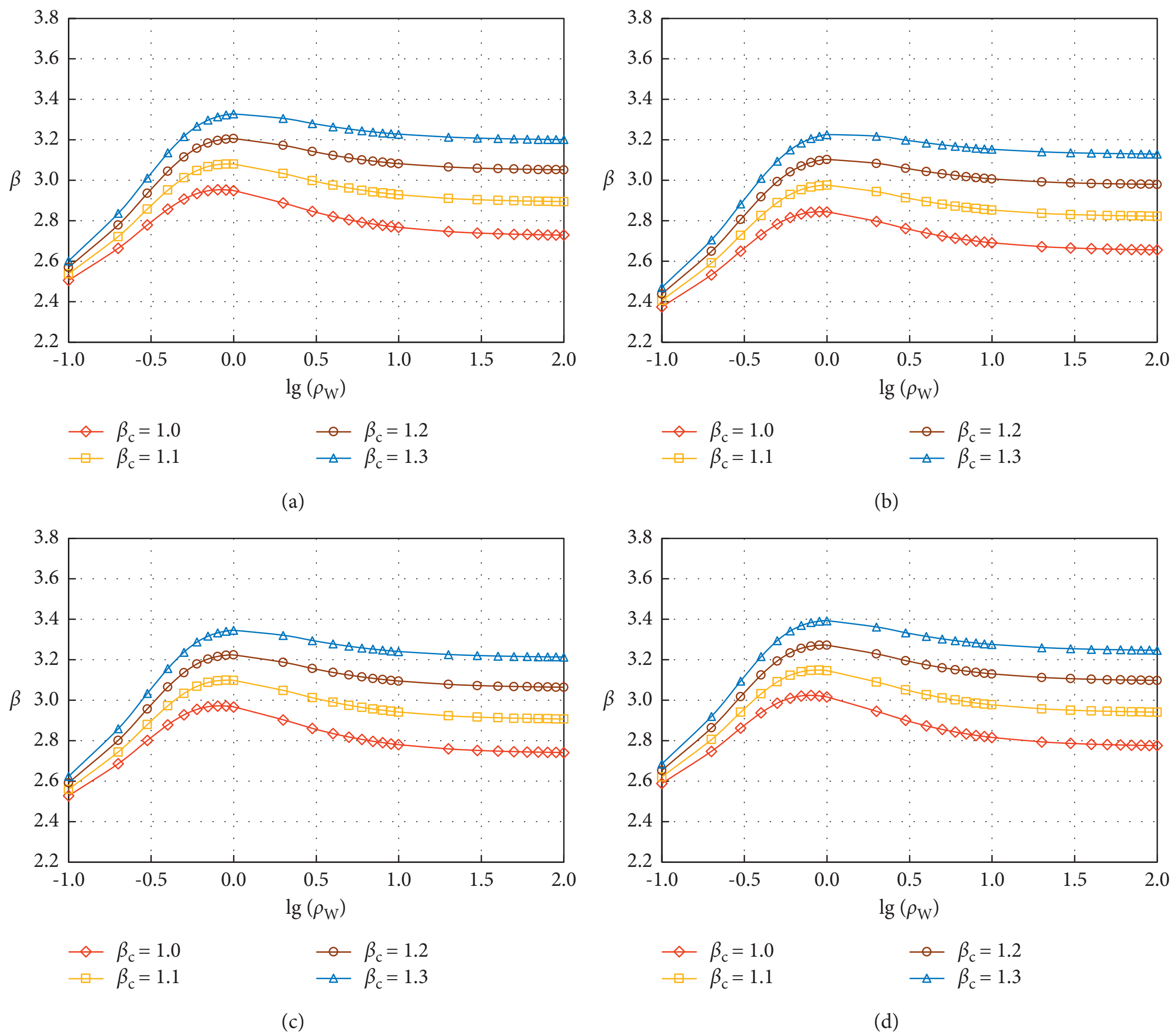

Figure 3: Reliability indices for stability calculation of axially loaded member. (a) Q235: $d > 16\sim40$ mm, (b) Q235: $d > 40\sim60$ mm, (c) Q345: $d > 16\sim35$ mm, and (d) Q345: $d > 35\sim50$ mm.

Table 7: The average value of reliability indices of different steel class.

Component type	βc	Q235		Q345	
		$d > 16\sim40$ mm	$d > 40\sim60$ mm	$d > 16\sim35$ mm	$d > 35\sim50$ mm
Strength calculation of axially loaded member	1.0	2.8918	2.7907	2.9092	2.9563
	1.1	3.0399	2.9396	3.0571	3.1039
	1.2	3.1815	3.0819	3.1985	3.2450
	1.3	3.3171	3.2181	3.3341	3.3803
Stability calculation of axially loaded member	1.0	2.7972	2.7049	2.8130	2.8561
	1.1	2.9358	2.8441	2.9515	2.9944
	1.2	3.0683	2.9772	3.0840	3.1266
	1.3	3.1954	3.1047	3.2109	3.2533

Therefore, safety classes of engineering structure are usually defined by a qualitative analysis method combined with engineering experience. Safety of engineering structure can be classified into three classes in design codes of many countries, such as Eurocode "Basis of structural design (EN 1900:2002)" [19] and Chinese standard "Unified standard for reliability design of engineering structures (GB 50153–2008)" [15]. Therefore, Classes 1, 2, and 3 are specified for transmission line crossing high-speed railway, with Class 1 being the strongest. Tension section across high-speed railway is defined as Class 1, tension section not crossing high-

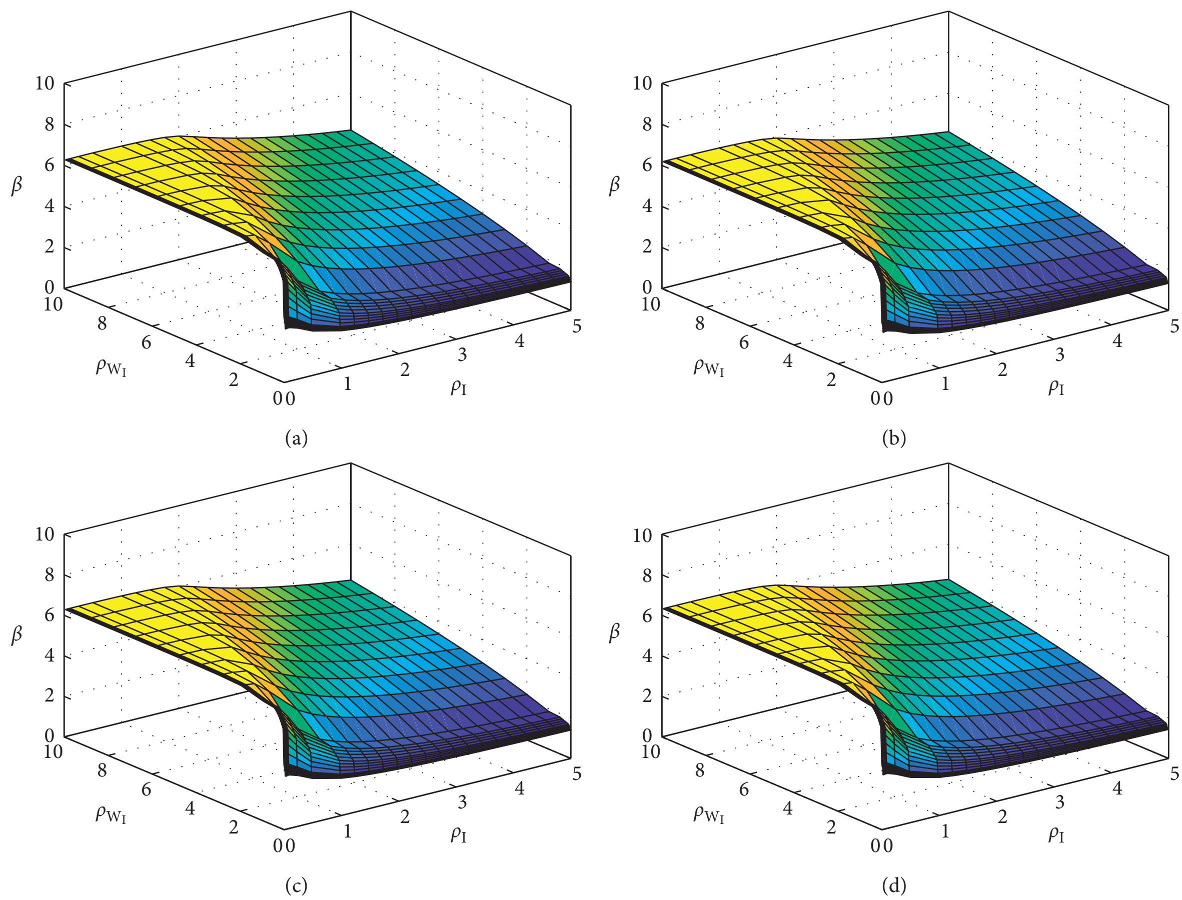

Figure 4: Reliability indices for strength calculation of axially loaded member. (a) Q235: $d > 16\sim40$ mm, (b) Q235: $d > 40\sim60$ mm, (c) Q345: $d > 16\sim35$ mm, and (d) Q345: $d > 35\sim50$ mm.

speed railway is defined as Class 2, and temporary line is defined as Class 3.

4.2.2. Recommendation of Target Reliability Index. The numerical values of the reliability are often described on the basis of the reliability index β defined by $\beta = -\Phi^{-1}(P_f)$, in which P_f is the failure probability. The relationship between β and P_f is given in Table 11. It is well recognized that the safety degree of engineering structure is medium and high for $10^{-3} < P_f < 10^{-4}$ and $10^{-4} < P_f < 10^{-5}$ [20].

Calibration method is a very simple and practicable method applied to define the structural safety level. Therefore, target levels for reliability are often based on calibration [20]. Target reliability indices β_T (i.e., recommended minimum values for reliability index) stipulated in Eurocode "EN 1900:2002" [19] and Chinese standard "GB 50153–2008" [15] are listed in Table 12.

As can be seen in Table 12, there is a difference of about 0.5 for reliability indices between the adjacent safety classes, while the probability of failure can approximately differ by an order of magnitude.

Based on the above section, the acceptable safety level of transmission tower Class 2 should be in agreement with the average reference values described in Table 10. Thus, a target reliability index of 3.2 is suggested for Class 2. Then a reliability index of 3.7 is recommended for Class 1 in this study for the reason that adjacent safety classes have a difference of about 0.5 for reliability indices. Since transmission line of Class 3 is temporary, functional failure does not lead to serious consequences, reliability can be reduced accordingly. Consequently, a reliability index of transmission tower for Class 3 can be 2.7.

5. Discussion

tIn order to determine the reliability of transmission line across high-speed railway, reliability calibration for steel angle tower of transmission line satisfying the minimum design requirements specified by Chinese codes was performed. The reliability indices of the tower for the extreme wind load case and the combined wind and ice load case are shown in Figures 2–5, respectively. Based on the aforementioned results, some discussions are provided as follows:

(1) In the extreme wind load case, reliability indices for strength calculation of axially loaded member approximately range from 2.60 to 3.61, whereas the indices for stability calculation of axial compression

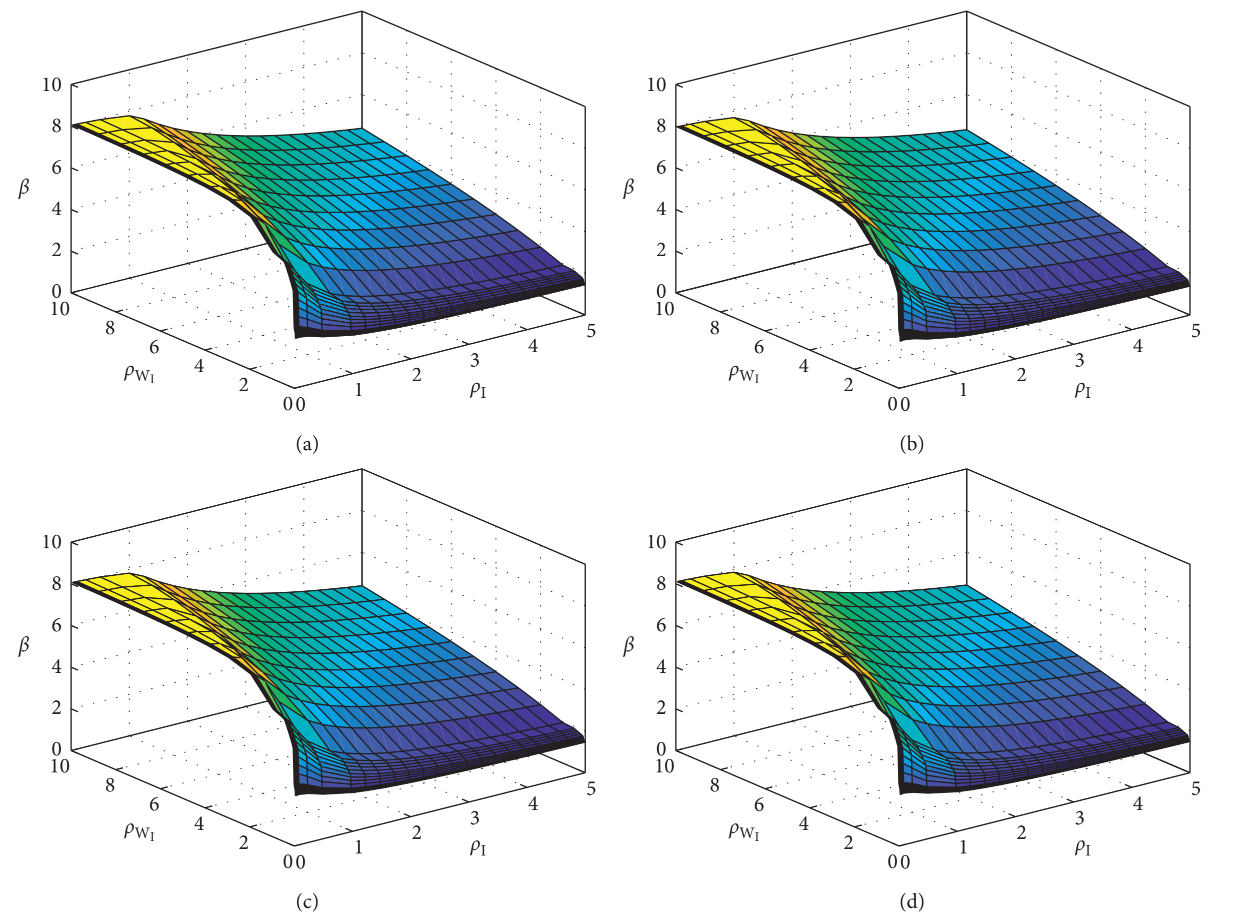

Figure 5: Reliability indices for stability calculation of axially loaded member. (a) Q235: $d > 16{\sim}40$ mm, (b) Q235: $d > 40{\sim}60$ mm, (c) Q345: $d > 16{\sim}35$ mm, and (d) Q345: $d > 35{\sim}50$ mm.

Table 8: Reliability indices of member of different steel classes.

Class	Steel thickness	Strength calculation	Stability calculation
Q235	$d > 16{\sim}40$ mm	3.3526	3.2025
	$d > 40\ {\sim}60$ mm	3.2526	3.1125
Q345	$d > 16{\sim}35$ mm	3.3697	3.218
	$d > 35{\sim}50$ mm	3.4165	3.2602

Table 9: Summary of reliability calibration results of transmission tower.

Types	Load case	$\beta_c = 1.0$	$\beta_c = 1.1$	$\beta_c = 1.2$	$\beta_c = 1.3$	Average value
Strength calculation	Extreme wind load	2.8870	3.0351	3.1767	3.3124	3.1028
	Wind load + ice load	3.3479	—	—	—	3.3479
Stability calculation	Extreme wind load	2.7928	2.9315	3.0640	3.1911	2.9949
	Wind load + ice load	3.1983	—	—	—	3.1983

Table 10: Reference value β_0 of transmission tower.

Types of tower member	Load case	β_0
Strength calculation	Extreme wind load	3.10
	Wind load + ice load	3.40
Stability calculation	Extreme wind load	3.00
	Wind load + ice load	3.20
Average value		3.18

Table 11: Relationship between β and P_f.

β	2.7	3.1	3.2	3.5	3.7	4.0	4.2
P_f	3.5×10^{-3}	1×10^{-3}	6.40×10^{-4}	2.33×10^{-4}	1.1×10^{-4}	3.17×10^{-5}	1.3×10^{-5}

Table 12: Target reliability indices stipulated in EN 1900:2002 and GB 50153–2008 (ultimate limit state, 50 year reference period).

Codes		Safety classes	β_T
EN 1900:2002 [19]		RC3	4.3
		RC2	3.8
		RC1	3.3
GB 50153–2008 [15]	Ductile failure	Class 1	3.7
		Class 2	3.2
		Class 3	2.7
	Brittle failure	Class 1	4.2
		Class 2	3.7
		Class 3	3.2

member range from 2.38 to 3.40, as can be seen in Figures 2 and 3. Correspondingly, reliability indices in the combined wind and ice load case are 1.32 to 6.31 and 1.39 to 8.09. The results indicate a wider range of reliability, probably due to the wide ranges of ρ_w and ρ_I. Furthermore, the ice load effect ratio ρ_I plays an important role in the reliability of tower, as shown in Figures 4 and 5.

(2) The reliability calibration results for the American National Electrical Safety Code (NESC C2-2002) and the Canadian Standard Association (CSA C22.3 No.1–2001) were presented in Ref. [4]. The reliability indices of transmission tower designed by NESC in the extreme wind load ranges from 2.36 to 3.01, whereas the indices for the combined wind with ice load case ranges from 2.29 to 3.91. Correspondingly, the reliability indices of transmission tower designed by CSA are 0.85 to 2.00 and 1.68 to 2.78, respectively.

It can be seen that the reliability level of transmission tower designed by Chinese code is about similar with that specified in NESC and higher than that specified by CAS for extreme wind load case and the combined wind and ice load case.

(3) There are some deficiencies in statistical parameters used for the reliability analysis in this work. Ideally, the statistical data of various load effects, such as wind load and ice load used for the reliability analysis should be obtained from the field. However, due to the lack of such information required, an alternative approach was used in this work. For instance, parameters of building structure stipulated in Chinese code were used as statistical parameters of permanent load and wind load in the extreme wind load case. Statistical parameters of wind load in the combined wind and ice load were derived by 50 year return annual maximum wind speed. Parameters of ice load were determined based on a statistical analysis of limited field data. Statistical parameters of resistance of tower for stability calculation were derived by considering the uncertainty of stability coefficient.

(4) The calibration results show that the reliability level of tower satisfying the minimum requirements in Chinese code needs to be improved. In this study, the recommended target reliability indices were given based on the average reliability indices obtained from reliability calibration and the recommended values of engineering structures suggested in the codes of many countries.

6. Conclusions

Based on the analysis results obtained, the following conclusions can be drawn:

(1) The reliability indices achieved lie within a large range, which may be caused by a wide range of ρ_w and ρ_I. The reliability level of transmission tower is similar with that of American standards but higher than that of Canadian specifications.

(2) The average reference value of reliability index was taken as approximately 3.2. The acceptable safety level of transmission tower Class 2 should be in agreement with this value.

(3) Classes 1, 2, and 3 were specified for transmission line crossing high-speed railway, with Class 1 being the strongest. For tower of transmission line across high-speed railway, the target reliability indices of Class 1, Class 2, and Class 3 were recommended as 3.7, 3.2, and 2.7.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of Shandong Provincial Natural Science Foundation, China and Natural Science Foundation of Liaocheng University.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This material is based on work supported by the Shandong Provincial Natural Science Foundation, China (Grant no. ZR2018BEE046) and Natural Science Foundation of Liaocheng University (Grant no. 318012111).

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