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

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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:

$$
\mu_{wt} = \frac{\ln(t/T) + \alpha_{WT}}{\sigma_{WT}} = \mu_{WT} + \frac{\sigma_{WT} \ln(t/T)}{1.2826}
$$

$$
= 0.908W_k + \frac{0.1752W_k \times \ln(1/12/50)}{1.2826}
$$

(1)

where $\mu_{wt}$ is the mean of wind load for the combined wind and ice load case; $\mu_{WT}$ and $\sigma_{WT}$ are the mean and standard deviation of wind load in the extreme wind load case, respectively; $\alpha_{WT}$ 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 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
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

\[ R = \Omega_p m A f, \]  

(2)

where \( \Omega_p \) 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 estimated as follows:

\[ k_R = \frac{\mu_R}{R_k} = k_p \frac{\mu_{k_A} \mu_{k_f}}{m k_A k_f}, \]  

(3)

\[ \delta_R = \sqrt{\delta_{\mu_R}^2 + \delta_{\mu_{k_A}}^2 + \delta_{\mu_{k_f}}^2}, \]  

(4)

in which \( k_p, k_A, \) and \( k_f \) as well as \( \delta_{\mu_R}, \delta_{\mu_{k_A}}, \) and \( \delta_{\mu_{k_f}} \) denote, respectively, the bias factor and COV of each calculation model, cross-sectional area, and material strength of tower members, as shown in Table 1 [18]; \( f_y, k_A, \) 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, \( k_R = 1.134 \) and \( \delta_R = 0.117. \)

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

\[ R = \Omega_p \phi m A f, \]  

(5)

where \( \phi \) is the stability coefficient of axial compression tower member and \( m_A \) is the stability reduction factor of compression chord member.

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

\[ k_R = \frac{\mu_R}{R_k} = k_p \frac{\mu_{\phi} m_A \mu_{k_f}}{A \phi k_A k_f}, \]  

(6)

\[ \delta_R = \sqrt{\delta_{\mu_R}^2 + \delta_{\mu_{\phi}}^2 + \delta_{\mu_{k_A}}^2 + \delta_{\mu_{k_f}}^2}, \]  

(7)

where \( \phi, \delta_\phi \) are the bias factor and COV of \( \phi \). Statistical parameters of \( \Omega_p \) in (6) and (7) are listed in Table 2 [18]. Statistical parameters of \( \phi \) shown in Table 2 are derived by the following method.

According to Chinese code DL/T5154–2012 [11], \( \phi \) can be calculated as

\[ \phi = \begin{cases} 1 - \alpha_1 \lambda^2 & \text{if } \lambda \leq 0.215 \\ \frac{1}{2\lambda^2} \left[ \left( \alpha_2 + \alpha_3 \lambda + \lambda^2 \right) - \sqrt{\left( \alpha_2 + \alpha_3 \lambda + \lambda^2 \right)^2 - 4\lambda^2} \right] & \text{if } \lambda > 0.215 \end{cases}, \]  

(8)

where \( \lambda \) is the slenderness ratio of tower member; \( f_y \) is steel yield strength; \( E \) is elastic modulus of steel; and \( \alpha_1, \alpha_2, \) and \( \alpha_3 \) are factors specified in Chinese code DL/T 5154–2012 [11].

Since the stability coefficient \( \phi \) shown in (8) is a piecewise function, the definition of probability distribution function and statistical parameters of \( \phi \) are complicated. In order to determine the statistical parameters of the stability coefficient \( \phi \), 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 \( 2 \times 10^5 \) 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 \( \phi \). According to the aforementioned statistical analysis, the statistical parameters of \( \phi \) for \( \lambda \) 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 \( \phi/\phi_k \) is depicted in Figure 1, where \( \phi_k \) is the characteristic value of \( \phi \). The bias factor of \( \phi \) is equal to 1.025, COV of \( \phi \) is equal to 0.068, as listed in Table 3.
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.

| Section type | λ | Steel thickness $d > 16$  \~ 40 mm | Steel thickness $d > 40$  \~ 60 mm | Steel thickness $d > 16$  \~ 35 mm | Steel thickness $d > 35$  \~ 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 | 1.152 | 0.001 | 1.148 | 0.001 | 1.186 | 0.001 | 1.177 | 0.001 |
| Section b    | 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| | 1.023 | —     | 1.022 | —     | 1.027 | —     | 1.026 | —     |

**Table 3: Bias factor and COV of $\phi/\phi_k$.**

**Figure 1:** Frequency histogram of $\phi/\phi_k$ 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.
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:

\[ \begin{align*}
    c_0 c_G S_G G_k + \psi c_Q S_Q k &\leq R_d, \\
    (10)
\end{align*} \]

where \( c_0 \) 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; \( c_G \) is the partial safety factor of permanent load, not more than 1.1 in favorable conditions, 1.2 in unfavorable conditions; \( c_Q \) is the partial safety factor of variable load \( Q_k \) taken as 1.4; \( S_G, S_Q k \) 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]; \( \psi \) 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

\[ R_d = y_0 \left( y_G S_G G_k + \psi \sum y_Q S_Q k \right) \]  \( \leq R_d \).  \( \text{(11)} \)


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

| Variables          | Statistical parameters | Probability distribution |
|-------------------|------------------------|--------------------------|
| Load effect       | \( k \) \( \delta \)   |                          |
| Permanent load    | 1.060 0.070            | Normal distribution      |
| 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              |
| Stability calculation | 1.185 0.150          | Lognormal distribution   |

Substitution of (13) into (11) leads to

\[ y_0 (y_G N_G G_k + \psi \sum y_Q N_Q k) = mA_n f_d, \] \( \text{(14)} \)

\( N = R_d = mA_n f_d \). \( \text{(13)} \)

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]

\[ \frac{N}{A_n} \leq m f_d, \] \( \text{(12)} \)

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:

\[ Z = R - N_G - N_W, \] \( \text{(17)} \)

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

\[ \mu_{N_G} = k_{N_G} N_{Gk}, \sigma_{N_G} = \delta_{N_G} k_{N_G} N_{Gk}, \]

\[ \mu_{N_W} = k_{N_w} \rho_W N_{Gk}, \sigma_{N_W} = \delta_{N_w} k_{N_w} \rho_W N_{Gk}, \]

where \( k_{N_G}, k_{N_w}, \delta_{N_G}, \) and \( \delta_{N_w} \) are the bias factors and COV of permanent load and wind load, respectively; \( \rho_W \) 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 \( \rho_W = N_{WI}/N_{Gk}. \)

The mean of resistance can be expressed as follows:

\[ \mu_R = k_R R_k = k_R (m N_{Gk} f_d) \frac{f_k}{f_d} \]

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

| Steel thickness (mm) | Q235     |     | Q345     |     |
|---------------------|----------|-----|----------|-----|
| d ≤ 16              | f_k (MPa)| 235 | f_d (MPa)| 235 |
| d > 16 ~ 40         | f_k (MPa)| 235 | f_d (MPa)| 235 |
| d > 40 ~ 60         | f_k (MPa)| 235 | f_d (MPa)| 235 |
| d > 60 ~ 100        | f_k (MPa)| 235 | f_d (MPa)| 235 |

The performance function of transmission tower member for strength calculation is always lower than those for stability calculation.

\[ Z = R - N_G - N_{WI} - N_1. \]

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:

\[ \mu_{N_{WI}} = k_{N_{WI}} \rho_{WI} N_{Gk}, \sigma_{N_{WI}} = \delta_{N_{WI}} k_{N_{WI}} \rho_{WI} N_{Gk}, \mu_{N_1} = k_{N_1} \rho_I N_{Gk}, \sigma_{N_1} = \delta_{N_1} k_{N_1} \rho_I N_{Gk}, \]

where \( k_{N_{WI}}, k_{N_1}, \delta_{N_{WI}}, \) and \( \delta_{N_1} \) are, respectively, the bias factors and COV of wind load and ice load in the combined wind and ice load case; \( \rho_{WI} \) is the wind load effect ratio, \( \rho_{WI} = N_{WI}/N_{Gk} \); \( \rho_I \) is the ice load effect ratio; \( \rho_I = N_{I}/N_{Gk}. \)

According to Table 6, \( \beta_c \) 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:

\[ \mu_R = k_R \frac{f_k}{f_d} [Y_G + \gamma_Q \rho_{WI} + \gamma_Q \rho_I] N_{Gk}. \]

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 \( \rho_W \) rather than the specific value of load effects and resistance. Analyses of numerous actual power transmission towers have shown that the ratio \( \rho_W \) 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 \( \beta \) of tower members for various steel classes with different wind load adjustment factors \( \beta_c \) 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 \( \beta_c \) are summarized in Table 7.

It can be seen from Figures 2 and 3 that the reliability indices of power transmission tower members relate directly to the ratio \( \rho_W. \) For \( \rho_W \leq 1.0, \) the reliability indices for strength calculation of axially loaded tower members increase with the increased \( \rho_W; \) meanwhile, for \( \rho_W > 1.0, \) the reliability indices decrease with the increased \( \rho_W. \) As shown in Table 7, the average values of reliability indices increase with the wind load adjustment factor \( \beta_c \), 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:

\[ Z = R - N_G - N_{WI} - N_1. \]

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:

\[ \mu_{N_{WI}} = k_{N_{WI}} \rho_{WI} N_{Gk}, \sigma_{N_{WI}} = \delta_{N_{WI}} k_{N_{WI}} \rho_{WI} N_{Gk}, \mu_{N_1} = k_{N_1} \rho_I N_{Gk}, \sigma_{N_1} = \delta_{N_1} k_{N_1} \rho_I N_{Gk}, \]

where \( k_{N_{WI}}, k_{N_1}, \delta_{N_{WI}}, \) and \( \delta_{N_1} \) are, respectively, the bias factors and COV of wind load and ice load in the combined wind and ice load case; \( \rho_{WI} \) is the wind load effect ratio, \( \rho_{WI} = N_{WI}/N_{Gk} \); \( \rho_I \) is the ice load effect ratio; \( \rho_I = N_{I}/N_{Gk}. \)

According to Table 6, \( \beta_c \) 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:

\[ \mu_R = k_R \frac{f_k}{f_d} [Y_G + \gamma_Q \rho_{WI} + \gamma_Q \rho_I] N_{Gk}. \]
As can be seen in Figures 4 and 5, when the ice load effect ratio $\rho_I$ is taken a fixed value, the reliability indices increase with the ratio $\rho_{WI}$, while the reliability indices decrease with $\rho_I$ in the case of a fixed wind load effect ratio $\rho_{W}$. Since the reliability in the combined wind and ice load case is governed mainly by $\rho_I$, a higher reliability level is produced for $\rho_{WI} > 0.1$ and $\rho_I < 0.1$, 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 $\beta_0$. 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 $\beta_T$

4.2.1. Safety Classes. In general, it is difficult to quantitatively calculate the loss due to structural failure.
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-speed railway is defined as Class 2.
4.2.2. Recommendation of Target Reliability Index. The numerical values of the reliability are often described on the basis of the reliability index $\beta$ defined by $\beta = -\Phi^{-1}(P_f)$, in which $P_f$ is the failure probability. The relationship between $\beta$ 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 $\beta_T$ (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

In 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: $d > 16\sim40$ mm, (b) Q235: $d > 40\sim60$ mm, (c) Q345: $d > 16\sim35$ mm, and (d) Q345: $d > 35\sim50$ mm.

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

| Class | Steel thickness | Strength calculation | Stability calculation |
|-------|-----------------|----------------------|----------------------|
| Q235  | $d > 16\sim40$ mm | 3.3526 | 3.2025 |
|       | $d > 40\sim60$ mm | 3.2526 | 3.1125 |
| Q345  | $d > 16\sim35$ mm | 3.3697 | 3.218 |
|       | $d > 35\sim50$ mm | 3.4165 | 3.2602 |

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

| Types | Load case | $\beta_0 = 1.0$ | $\beta_1 = 1.1$ | $\beta_1 = 1.2$ | $\beta_1 = 1.3$ | 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 $\beta_0$ of transmission tower.

| Types of tower member | Load case | $\beta_0$ |
|-----------------------|-----------|-----------|
| 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 |
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 range of $\rho_w$ and $\rho_I$. Furthermore, the ice load effect ratio $\rho_I$ 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 (NESC2-2002) 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 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 $\rho_w$ and $\rho_I$. 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.

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