Bearing Capacity Analysis of Transmission Tower Structure Considering Corrosion Damage

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Abstract. As an important part of power grid equipment, transmission towers are in direct contact with the external environment for a long time. As a coastal city in China, Fujian has been affected by marine environment and industrial pollution for a long time, which directly affects the safety of transmission towers in long-term service. In order to explore the changes of the ultimate bearing capacity of the tower structure after corrosion, this paper uses finite element software to analyse the mechanical properties of the tower structure during long-term service, and finds that the 45° wind direction is the control condition, and the overall stiffness of the tower decreases with the growth of corrosion time, and the increment of tower top displacement reaches 7% at 12 years of corrosion. The corrosion-sensitive members of the tower were clearly identified, and their stress ratios increased from 0.78, 0.79, and 0.83 to 0.97, 0.98, and 0.99, respectively, at 12 years of corrosion.

1. Introduction
As an important part of the power grid equipment, transmission towers are usually made of lightweight and high-strength steel structure, whose safety and reliability are the basis for ensuring the safe and stable operation of the power grid, and is also a key part of the "three types of two networks" construction goal. However, with the rapid development of China's power system construction and service time growth at the same time, the operation of transmission towers has some safety hazards.

Chen Weiming et al. studied the load carrying capacity of transmission pylons underground deformation in different directions [1], Yu Cong et al. studied the effect of transmission pylon systems on ultimate load carrying capacity under different wind angles [2], Dai Kaoshan et al. studied the form of failure of transmission pylon systems under combined earthquake and wind loads [3], Wang Jia et al. studied the ultimate load carrying capacity of pylons with local defects [4], Zhang Yihu et al. studied the form of transmission tower damage when considering nonlinearity [5], and Jian Zhang et al. studied the form of failure of transmission towers under strong wind loads [6]. All the above studies are based on external load effects.

Fujian Province is located in the southeast coast with hot and humid climate, and its transmission towers have been affected by the marine environment for a long time, coupled with serious industrial pollution and frequent acid rain in recent years, its corrosion environment is quite different from other regions. Secondly, the current research on towers is limited to the material level, and the relationship between the material properties after corrosion and the performance deterioration of the tower structure has not been established. In this paper, by establishing a finite element model of a typical tower structure and introducing a typical corroded material degradation ontology, the mechanical property degradation law of the tower structure under corrosive environment is systematically analysed, and suggestions are made for the operation and maintenance of the tower.
2. Project Overview
In this paper, we choose the transmission level of 220kV general tension-resistant tower, model JC2-30, transporting double circuit, alternating current, recorded as N1 tower (hereinafter referred to as N1). N1 tower’s front gear distance 700m, rear gear distance is 300m, the total height of the tower 47.7m, and the N1 tower as the center of the establishment of the line tower system model, as shown in figure 1. The nodes are connected by high strength bolts, and the foundation is inserted is the foundation. The ground wire in the line tower system is TS_JLB20A-150, with an average running tension ratio of 0.18 and a cross section of 148[mm]^2, the average height of the ground wire is 15m, and the conductor is JL/LB20A-630/45 with an average running tension ratio of 0.25 and a cross section of 666.55[mm]^2 . The average height of the conductor is 15m, and the specific dimensional information of the tower is shown in figure 2.

![Figure 1. Schematic diagram of line tower system (mm).](image1)

(a) Tower composition  (b) Cross arm composition

![Figure 2. Overall schematic diagram of the tower (mm).](image2)

(a) 3D3S Model (b) Name of Tower Member

![Figure 3. Tower model.](image3)
3. Finite Element Model

3.1. Model Establishment

The tower model is established based on the tower design module selected in 3D3S software. The tower is a system of one tower and two lines (as shown in table 1). In the software, the tower model library provided by the software is used to establish the model, and the key members and material information of the tower are added. The types of tower members are tower columns, sway rods, secondary sway rods, cross bars, web members, chords and other main components. The cross sections of members are equilateral angle steels, as shown in table 1 and figure 3.

| Member name         | sections                      | materials   |
|---------------------|-------------------------------|-------------|
| Tower column        | L200×20, L180×16, L140×12     | Q420B       |
|                     |                               | Q345B       |
| Sway rod            | L140×10, L125×10, L110×10, L100×10 | Q345B       |
|                     | L100×8, L100×7, L90×7, L90×6 |             |
| Secondary sway rod  | L63×5, L40×4, L40×3           | Q235B       |
| Cross bar           | L63×5, L40×3                  | Q235B       |
| Web member          | L90×7, L63×5, L56×5, L45×4, L40×3 | Q345B   |
|                     |                               | Q235B       |
| Other               | L20×3, L40×3, L40×4, L45×4, L56×6, L63×5 | Q345B   |
|                     | L75×5, L75×6, L80×6, L90×6, L75×10 | Q235B     |

3.2. Boundary Condition

Inputing the basic wind pressure in the loading module of the software. According to the “Load code for building structure” GB50009-2012, the basic wind pressure should use the basic wind pressure with a return period of 50 years. When the transmission tower is calculated in 3D3S structural design software, the ground roughness is class B, the wind load calculation code is high-rise code, the building structure type is high-rise structure, the house type is non maintenance steel structure, and the terrain is flat. Connection between tower and foundation is rigid connection. According to the relevant standards and requirements of code for design of 110kV ~ 750kV overhead transmission lines (GB 505445-2010), the basic wind pressure is calculated according to formula (1).

$$W_0 = \frac{V^2}{1600}$$  \hspace{1cm} (1)

W0 is the standard value of reference wind pressure and V is the wind speed with height of 10m.

According to the control standard for basic wind speed conditions of tension type tower load in GB 505445-2010 and considering the influence of wind speed, tower height and tower type of transmission tower, this paper only checks and calculates the four working conditions of wind load of 0 °, 45 °, 60 ° and 90 ° under strong wind, and the schematic diagram is shown in figure 4. Since the structure is a non-maintenance steel structure, and the member type of the tower tip is a truss element, and the member is only subjected to axial force, the load acts directly on the node, as shown in figure 4 (b). The load bearing direction and range of wind load under four working conditions of tower 0 °, 45 °, 60 ° and 90 ° are shown in figure 5.
The parabolic model in the literature [3] is used for the linear tower system model, as shown in figure 6. Taking the left hanging line point A as the origin, the horizontal line passing through point A as the x-axis, and the left vertical downward line as the y-axis, then the relationship is shown in formula (2). The horizontal tension, approximate values of conductor and ground wire length and approximate values of conductor and ground wire tension can be calculated by the same formula (3)(4). Table 2 for conductor tension.

\[ y = \frac{4fx(l-x)}{l^2} + \frac{h}{l} x \]  \hspace{2cm} (2)

Relationship between mid-span sag and horizontal tension:

\[ H = \frac{ql^2}{6f \cos \theta} \]  \hspace{2cm} (3)

Approximate cable length:
\[ S = L \left[ 1 + \frac{1}{2} \left( \frac{h}{L} \right)^2 + \frac{8}{3} \left( \frac{f}{L} \right)^2 \right] \]  

Approximate maximum cable tension:

\[ T = H \sqrt{1 + 16 \left( \frac{f}{L} \right)^2 + \frac{h^2}{L^2} + \frac{8fh}{L^2}} \]  

Model of tower system \( q \) is the unit load along the conductor and ground wire, \( h \) is the height difference of suspension point, and \( f \) is the mid span sag.

The standard values of wind load of conductor and ground wire and wind load of insulator string are calculated according to relevant standards of “code for design of 110kV ~ 750kV overhead transmission lines” (GB 50545-2010). The standard value of horizontal wind load of conductor and ground wire shall be calculated according to formula (6), and the standard value of wind load of insulator string shall be calculated according to formula (11) without considering icing.

\[ W_x = \alpha_L \mu_2 \mu_a \mu_c W_0 \beta_c dL_p \sin^2 (\theta) \]  

\[ \beta_c = \gamma_c (1 + 2g \cdot I) \]  

\[ I = I_{10} \cdot \left( \frac{z}{10} \right)^{-\alpha} \]  

\[ \alpha_L = \frac{1+2g \cdot c \cdot I_p L_p}{1+5L_p} \]  

\[ \delta_L = \frac{1}{3} \left[ \frac{L_p^2}{3L_p^2 + 54L_p^2 - 36L_p^2 L_p - 72L_p^2 e^{L_p} + 18L_p^2 e^{L_p}} \right] \]  

\[ W_f = \mu_z W_0 A_f \]  

\( W \) is the sum of the standard values of wind load of conductor and insulator string. \( W_x \) is the standard value of horizontal wind load perpendicular to the direction of conductor and ground wire. \( \alpha_L \) is the span reduction coefficient. \( \beta_c \) is the gust coefficient of conductor and ground wire, where 1.0 is taken. \( \mu_z \) is the wind pressure height variation coefficient. \( \mu_a \) is the shape coefficient of conductor and ground wire. \( d \) is the outer diameter of conductor and ground wire. \( L_p \) is the horizontal span of tower. \( \theta \) is the included angle between wind direction and conductor and ground wire. \( W_0 \) is the standard value of reference wind pressure. \( V \) is the basic wind speed with a reference height of 10m. \( W_f \) is the standard value of wind load of insulator string. \( A_f \) is the calculated value of wind pressure bearing area of insulator string.

The vertical load, horizontal load and tension load on the front and rear sides of the conductor and ground wire act on the tower and act on the hanging point according to the node load. The vertical load is the load generated by the icing along the length of the conductor and the dead weight of the insulator string on the conductor and ground wire, and the direction is vertical and downward. Horizontal load is the load of conductor, ground wire and insulator string under wind load, and the tension is perpendicular to the tower along the conductor direction, as shown in figure 7. The calculated load is shown in table 2.

**Table 2. Load at hanging point.**

| name       | \( f (m) \) | \( q (N/m) \) | Tension load(N) | horizontal load(N) | Vertical load(N) |
|------------|-------------|---------------|----------------|--------------------|-----------------|
| wire 1 / 2 front | 14.01      | 16.6676       | 41884          | 8192               | 8183            |
| wire 1 / 2 rear  | 2.33       | 16.6676       | 38073          | 3851               | 2156            |
| Wire 1 / 4 front | 24.20      | 32.7282       | 110359         | 28664              | 31867           |
| Wire 1 / 4 rear  | 4.45       | 32.7282       | 95951          | 13618              | 12380           |
| Wire 2 / 5 front | 24.20      | 32.7282       | 110359         | 27127              | 31867           |
| Wire 2 / 5 rear  | 4.45       | 32.7282       | 95951          | 12975              | 12380           |
4. Material Corrosion Damage Constitutive Model

After the model is established, the constitutive models of the main members and other members of the tower are modified in the material attribute module of the software and input according to the ideal elastic constitutive model. Based on the three-stage corrosion model of low alloy steel in [11], this paper analyses the relationship between mass loss and corrosion time of Q420B and Q345B in atmospheric environment. The first stage of the three-stage model is the rapid corrosion stage, the second and third stage is the corrosion mitigation stage. There are obvious differences in the corrosion models of the three stages. Kuang Jinxin studied the corrosion behavior of Q420 under atmospheric corrosion and accelerated corrosion. Based on the atmospheric corrosion data of low alloy steel in Jiangjin area of Chongqing, a three-stage mathematical model between mass loss and corrosion time is obtained as shown in formula (12): the corrosion time in the first stage is linear with the mass loss rate, the second stage is parabolic, and the third stage is also linear. Compared with the first stage, the corrosion rate becomes smaller.

\[
\rho_m = \begin{cases} 
2.09t & \text{if } t \leq 1 \\
-8.5^{-2}t^2 + 1.66t + 0.52 & \text{if } 1 \leq t \leq 8 \\
0.52t + 4.15 & \text{if } t \geq 8 
\end{cases}
\tag{12}
\]

w is the mass loss, t is the corrosion time, \(m\) is the mass before corrosion [11], \(\rho_m\) is the mass loss rate.[12]

By studying the corrosion behavior of Q235B in atmospheric environment and doing static tensile test on the corroded material, the changes of mechanical properties of the material are obtained. It is found that the elastic modulus, yield strength, tensile strength and mass loss rate of Q235B after corrosion have the following linear relationship, and the constitutive damage model of Q235B in atmospheric corrosion environment is established.

\[
\frac{f_{ny}}{f_y} = 1.011 - \beta_{nfy} \cdot \rho_m(\%) \quad \beta_{nfy} = 0.022 
\tag{13}
\]

\[
\frac{f_{nu}}{f_u} = 1.007 - \beta_{nfu} \cdot \rho_m(\%) \quad \beta_{nfu} = 0.015 
\tag{14}
\]

\[
\frac{E_c}{E} = 0.980 - \beta_E \cdot \rho_m(\%) \quad \beta_E = 0.004 
\tag{15}
\]

\(f_{ny}\) is the yield strength, \(f_{nu}\) is the ultimate tensile strength, \(E_c\) is the elastic modulus after corrosion, \(\beta_{nfy}\) is the reduction factor of nominal yield strength, \(\beta_{nfu}\) is the reduction factor of the nominal ultimate tensile strength.
Therefore, the above three-stage model and constitutive damage model are used to determine the damage constitutive models of Q420B, Q345B low alloy steel and Q235B after corrosion for 2, 4, 6, 8, 10 and 12 years, as shown in table 3.

| t   | $\rho_m$ | $f_y$ (MPa) | $f_u$ (MPa) | $E_c$ (GPa) | $f_y$ (MPa) | $f_u$ (MPa) | $E_c$ (GPa) | $f_y$ (MPa) | $f_u$ (MPa) | $E_c$ (GPa) |
|-----|----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 0   | 0        | 235.0       | 370.0       | 206         | 345.0       | 470.0       | 206         | 420.0       | 520.0       | 206         |
| 2   | 2.09     | 226.8       | 360.9       | 200.1       | 332.9       | 458.5       | 200.1       | 405.3       | 507.3       | 200.1       |
| 4   | 3.5      | 219.5       | 353.1       | 199.0       | 322.2       | 448.6       | 199.0       | 392.2       | 496.3       | 199.0       |
| 6   | 5.8      | 207.6       | 340.4       | 197.1       | 304.7       | 432.4       | 197.1       | 371.0       | 478.4       | 197.1       |
| 8   | 7.42     | 199.2       | 331.4       | 195.7       | 292.4       | 420.9       | 195.7       | 356.0       | 465.7       | 195.7       |
| 108 | 194.3    | 326.1       | 194.9       | 285.3       | 414.3       | 194.9       | 347.3       | 458.4       | 194.9       |
| 129 | 189.2    | 320.7       | 194.1       | 277.8       | 407.3       | 194.1       | 338.2       | 450.7       | 194.1       |

5. Results and Discussion

According to the finite element calculation results we can see that the direction of wind load 45 degrees controls the structure, the displacement of the top of the tower the internal force of structure internal bar is biggest at this time, therefore, the displacement of key points A, B, C and D in the structure in the wind load direction of 45 degrees and the change of stress ratio of key members 1, 2, 3 and 4 are selected. The positions of key points and key members in the tower are shown in figure 8.

The displacement of the top of the tower in X and Y directions is shown in Figure 9. Displacement in both directions increases with the increase of service time of tower, change trend can be divided into three stages, the stage I is a rapid growth stage (0~2 years), the stage II is faster growth stage (2~10 years), the stage III is slow growth phase (10 years~), among them, the displacement of the top of the tower in X direction reached 182mm after 12 years of service., the direction of the displacement Y direction displacement reached 33 mm, it can be inferred that the X direction plays a controlling role.
Figure 9. Relationship between lateral displacement of tower top and corrosion time.

Figure 10 shows the structure's displacement changes in the X direction. It can be seen that with the longer service time of the tower, the overall displacement of the tower shows an increasing trend, compared with the displacement of the initial structure, when the structure is in service for 12 years, the displacement of point A increases by about 7%, point B by about 6.5% and point C by about 6%. The curve can be divided into two stages with 2 years as the cut-off point. The stage I is 0-2 years, and its displacement growth rate is the fastest, the displacement of the structure has increased by about 4% after only two years of service, and the growth rate has gradually slowed down in 2-10 years, reaching 9% in 10 years, and then the growth rate has further decreased. This is because in the first two years of service, the corrosion degree of the main material of the tower is the largest, the change of the elastic modulus of the main material is the fastest, and the stiffness of the overall structure of the tower is the most reduced. As the corrosion time increases, protective rust layer is formed on the surface of the main material, and the corrosion rate decreases, it caused a decrease in the displacement change rate of the structure.

In figure 10(a) and (b), the relative positions of points A, B and C are opposite in the above two figures. During the same period of service, the overall displacement in the X direction of the same position is less than that of the overall structure in Y, which has a controlling effect on the tower. The figure shows that the overall Y-direction displacement of the structure gradually increases with the increase of service time. Its growth trend can be divided into two stages: the first stage is rapid growth, the second stage is slow growth. Take the second year as the demarcation point, two years before belongs to the rapid growth stage, two years after belongs to the slow growth stage. This is because the structure of advocate material corrosion rate at first, the fastest advocate material elastic modulus decreases faster, the overall stiffness decrease rate, along with the increase in time advocate material formed on the surface of protective rust layer, advocate material corrosion rate is reduced, the elastic modulus change rate is reduced, the structure of the whole stiffness change rate is reduced, displacement rate would decrease gradually. It can be seen from the figure that the change rate of the structure's displacement in the Y direction is the largest at point D, followed by two points B and C, and the smallest at point A. After 12 years of service, the displacement of the structure at Point A increases by about 7%, that at point B and C by about 8% and that at point D by about 11%. This is because in the initial state, the displacement of the whole structure in the Y direction is compared, but the displacement growth is the same.
Figure 10. Relationship between lateral displacement of typical parts and corrosion time.

Figure 11 shows the changes of the stress ratio of the rods. It can be seen that the stress of all the rods presents three growth stages: I, II and III, the stress before 6 years belongs to the rapid growth stage, and after 6 years belongs to the slow growth stage. This is because the corrosion rate in the initial stage of the tower main material is fast, the rate of reduction of the cross-sectional area of the tower components increases, and the rate of increase of stress ratio increases. With the increase of service time, a protective rust layer is formed on the surface of the tower main material, which reduces the corrosion rate of the material. The increasing rate of area loss rate decreases, for this reason the increasing rate of stress ratio decreases. In addition, in figure 3 and 4, curve of stress than similar trends, stress ratio were greater than 1 and 2, this is because in the structural design to ensure the bearing capacity of the lower structure is bigger than the upper structure, the material resistance of the lower member is larger than that of the upper member, and the residual value of the material resistance of the lower member is larger than that of the upper member under load. However, after 10 years, the stress ratio of No.2 is greater than that of No.3 and No.4, this is because when the stress ratio of No.3 and No.4 members reaches the limit load, other members share the load generated by the superstructure load. The stress ratio of No.2 bar is greater than that of No.1 bar, because No.1 bar bears tension and both bars bear pressure, and the stress on the section of No.2 bar is greater than that on No.1 bar. It is observed that after 12 years, the stress ratio of all members reaches about 1.

Figure 11. Relationship between stress ratio of key members and corrosion time.

6. Conclusion
The tower is in direct contact with the external environment for a long time during service. However, there is a large amount of acidic ions in the external environment, and the tower under the action of acidic ions the main material undergoes serious corrosive effects. Using 3D3S structural analysis software to analyze the displacement changes in the tower shut-in position and the stress ratio changes in the key bars of the transmission tower after corrosion, the following conclusions were drawn:

1. The overall trend of the growth rate of the lateral movement of the structure and the amount of lateral movement as the tower becomes longer in service can be divided into three phases, the
first phase is a rapid growth phase, the second phase is a faster growth phase, and the third phase is a slow change growth phase.

2. The displacement of the tower in the X-direction is greater than the displacement in the Y-direction when the wind load is 45 degrees wind load direction, and the X-direction plays a controlling role. As the tower becomes longer in service, the lateral displacement is gradually increasing, after 12 years of service the lateral displacement increases by 12 mm compared to uncorroded, with a growth rate of 7%, that is, the tower stiffness is also gradually decreasing.

3. As the time in service of the towers increased, all the bars reached stress ratios that gradually increased, from 0.78 to 0.97 for tower 1, from 0.79 to 0.98 for tower 2, and from 0.825 to 0.985 for towers 3 and 4 after 12 years in service.

Acknowledgments
This work is supported by research project of State Grid Fujian Economic Research Institute (No. B3130N210014).

References
[1] Chen W M, Chen W G, Wang X. 2015 Research on the influence law of ground deformation on transmission tower system in mining area [J] Steel Structure 30 (8) 38-42.
[2] Yu C, Li Z L, Wang Z S. 2018 Analysis of damage process of transmission tower line system under equivalent static wind load [J] Special Structures 35 (4) 38-45.
[3] Dai K S, Zhao Z, Meng J Y. 2021 Evaluation of failure probability of wind power towers under earthquake and wind loads [J] Engineering Science and Technology 53 (02) 38-44.
[4] Zhang Y H, Dai Y, Wang Y Q. 2019 Analysis of damage forms of power transmission towers in mining areas considering material nonlinearity [J] Jiangsu Construction (03) 24-28.
[5] Liu H Y, Li Z L, Huang Z L. Study on the compressive stability load bearing capacity of angular steel members of power transmission towers [J/OL] Advances in building steel structures 1-11 [2021-09-25].
[6] Qu K M, Li Z L, Huang Z L. 2021 Bearing capacity tests and finite element analysis of cross-slanting materials of transmission towers [J] Special Structures 38 (04) 73-84.
[7] Liu S, Huang Z, Yang Y, Zhang C, Gao Q S. 2020 Analysis of ultimate bearing capacity of transmission tower system under equivalent static wind load of typhoon [J] Journal of Disaster Prevention and Mitigation Engineering 40 (05) 757-763.
[8] Kuang J X. 2020 Study on impact resistance of Q420 steel pipe considering corrosion damage [D] Mianyang: Southwest University of Science and Technology.
[9] Wu H Y. 2020 Experimental and theoretical study of static and fatigue performance of structural steel based on atmospheric and accelerated corrosion correlation [D] Taiyuan University of Technology.
[10] Jafari M, Sarkar P P. 2021 Buffeting and Self-Excited Load Measurements to Evaluate Ice and Dry Galloping of Yawed Power Transmission Lines [J] Journal of Structural Engineering 147 (11).
[11] Jia J J, Liu C K, Jie L B, Shu Q J, Zhong C S, Yuan G L. Study on the deformation resistance of transmission tower line system in mining area under horizontal deformation of ground surface in different directions [J/OL] Industrial Building 1-8[2021-09-25].
[12] Fu C Y. 2021 Uncertainty response and collapse analysis of transmission tower-line system under earthquake [D] Shandong University.
[13] Zhong W J, Xu H W, Lou W J, Ma Y P, Guo G P. 2020 Wind vibration analysis of offshore high-voltage transmission structures under typhoon wind fields [J] Spatial Structure 26 (04) 91-96.
[14] Du W L. 2021 Theoretical, empirical and simulation studies on wind vibration coefficients of transmission lines under the action of typhoon [D] Dalian University of Technology.