Ultimate capacity analysis of transmission tower line system under wind load

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Abstract: As an important part of the large complex lifeline system, the transmission tower line system has many accidents. Based on the static and dynamic calculation theory, the response of the structure is analyzed, the ultimate capacity of the transmission tower system is obtained, and the weak position is studied, and the ultimate capacity of the transmission line is comprehensively evaluated. The result shows that the weak position is Segment 4 and 5 of the transmission tower, and the ultimate capacity of dynamic analysis is smaller than that of static analysis.

1. Introduction
As an important part of large complex lifeline system, the safety of transmission tower line system directly affects the production of the country and the order of people's life. The transmission tower has the characteristics of light weight, high flexibility and small damping, so the structural members will bucking or even yield, and the whole structure may collapse under wind load. In addition, China is a country with frequent wind disasters. Every year, typhoons, tornadoes and downbursts cause great losses to transmission lines, and accidents of transmission tower occur from time to time under wind load[1-3]. Therefore, it is a key problem to study the ultimate capacity of transmission tower under wind load to ensure the safety and reliability of it.

At present, many experts and scholars have adopted numerical simulation[4-7] and wind tunnel tests[8-11] to research the wind vibration response of transmission tower. However, there are still some difficulties in the research of the wind resistance of transmission line. The transmission tower will vibrate in coupling with the transmission line under wind load, showing the phenomenon of energy shift in different frequency regions. Therefore, when studying the response of transmission tower under wind load, the model of transmission tower line system must be used to analyze and obtain accurate calculation results. In addition, wind load is a kind of dynamic load, which has a dynamic effect on the structure. The coupling effect of tower line system will increase the dynamic response of the structure. Therefore, the ultimate capacity of tower-line system can be calculated more accurately by dynamic analysis.

Therefore, the FE model of single tower is established using ABAQUS and its stress characteristics and ultimate capacity are analyzed according to static calculation theory. The FE model of tower line system is established. The response of structure is analyzed based on dynamic theory.
2. Finite element model

2.1. FE model of transmission tower

This paper takes a typical transmission tower ZB433-32 of 500 kV Fuxu and Xugang as the case study, which is an angle steel tower, the main material is Q345, and the other elements are Q235. B31 element is used to simulate the angle steel members of the transmission tower, and the ideal elastic-plastic model is adopted. Each node has three translational degrees of freedom and three rotational degrees of freedom, and there is the seventh degree of freedom, that is, the warpage degree of freedom of the cross section. Therefore, any section of the beam has the ability of bearing tension, bending and torsion, which can simulate the linear, large angle rotation and nonlinear large deformation problems of open thin-walled elements. Therefore, it is very suitable for simulating mechanical characteristics of angle steel of towers.

The whole tower is divided into 8 parts and the Part is established, respectively. The interaction between Part is MPC-Beam, which limits the six degrees of freedom among the nodes. The FE model of the transmission tower is shown in figure 1.

![Figure 1. FE model of transmission tower](image)

2.2. FE model of transmission tower system

Transmission line is a typical cable structure, and its reaction has geometric nonlinear of large displacement and small strain. To establish the FE model of conductor and ground line, the initial configuration must be determined, and then the initial node coordinates of each cable element must be determined.

2.2.1. Determination of initial sag of transmission lines. There are two kinds of calculation theory: catenary theory and parabola theory. It is generally believed that catenary theory is an accurate theoretical method, while parabola theory is an approximate theoretical method. When the sag span ratio of cables is less than 1/8, the solution obtained can be considered to be acceptable using parabola theory. As a cable structure, transmission lines conform to the basic assumptions: 1) cable is ideal and flexible, can only withstand tension but not compression and bending; 2) material conforms to Hook's law. The sag span ratio of tower is 1/8, the parabola theory is adopted. The equilibrium equation of the cable is deduced according to two basic assumptions, and the initial spatial configuration of the conductor and ground line are determined.

2.2.2. Material parameter of transmission lines. The two span of transmission lines is 402m and 538m, and the parameters of lines are shown in table 1. T3D2 element is used to simulate transmission line. And the transmission line is divided into one element every 1 meter in the horizontal direction.
Table 1. Parameters of lines.

| Type       | Area   | Diameter | Expansion coefficient | Elastic modulus | Poisson's ratio | Sag    |
|------------|--------|----------|-----------------------|-----------------|-----------------|--------|
| Conductor  | JL/LB20A-300/40 | 1.36E-03 | 9.58E-02              | 2.06E-05        | 6.90E10         | 0.30   | 16.5336 |
| Ground     | OPGW-132 | 1.32E-04 | 1.54E-02              | 1.36E-05        | 1.37E10         | 0.30   | 12.6324 |

2.3. FE model of insulators

Insulator is a member connecting transmission line and tower. Its stiffness is large and the two ends are hinged in mechanics. It can be considered that it is only subjected to axial force. The insulator is simulated by T3D2, and each insulator is divided into one element.

![Figure 2. FE model of transmission tower line system](image)

The connection points of insulator, transmission lines and towers are all hinged, and the tower is fixed on the ground. Then, the FE model of tower line system is established, as shown in figure 2.

3. Static analysis of transmission towers

3.1. Model of insulators

The members of the angle steel tower basically keep in the axial force state. Therefore, in the eigenvalue buckling analysis of the tower, the most important thing is to find the external load to make the model stiffness matrix singular, and solve the problem:

\[
\left(K_N^{NM} + \lambda_i K_N^{NM}\right)v_i^M = 0
\]

where, \(K_0^{NM}\) is the initial stiffness matrix; \(K_\lambda^{NM}\) is the load stiffness matrix; \(\lambda_i\) is the eigenvalue; and \(v_i^M\) is the buckling mode shape. \(M\) and \(N\) refer to the degree of freedom.

Based on the above principle, the eigenvalue buckling analysis of the tower is conducted. The one to six modes are shown in figure 3, and the eigenvalues are shown in table 2. It can be seen from figure 3 that the failure positions of the first to sixth modes are all at the fourth and fifth segment of the tower, and it is preliminarily judged that Segment 4 and 5 are weak positions. In the following nonlinear buckling analysis, only the third and fourth order modes are taken as the initial defects, so as to avoid the phenomenon that the first and second order modes are involved and the defects set off against each other.

![Segment IV, V](image)

(a) first-order buckling mode  (b) second-order buckling mode  (c) third-order buckling mode

![Figure 3. Modes of transmission tower](image)
Table 2 shows that partial modal eigenvalues is negative. It indicate that if a load is applied in the opposite direction, the structure will buckle, which can be avoided by applying preload before analysis.

| Mode | 1    | 2    | 3    | 4    | 5    | 6    |
|------|------|------|------|------|------|------|
| eigenvalues | -2.4857 | -2.5141 | 2.5547 | 2.5792 | -2.6090 | -2.6238 |

3.2. Nonlinear buckling analysis of tower

A Static /Riks analysis step is used for load-deflection analysis. This method is usually used to predict the geometric nonlinear of structures. The analysis is usually based on eigenvalue buckling analysis to provide complete information about structural failure. The defects are defined by the superposition method based on weighted buckling mode shape. The initial defects are applied to the tower on the basis of linear buckling. The initial defects take the combination of 1/1000 of the third order mode and 1/500 of the fourth order mode. Taking the geometric nonlinearity into account, the Riks analysis step in the ABAQUS is used to calculate the ultimate capacity. The value of the ultimate load and the final failure form of the tower can be obtained by the analysis. The failure pattern of the tower obtained by nonlinear buckling analysis is shown in figure 4.

The ultimate wind speed is 44.4 m/s. The failure form reflects the large stress value of the tower at the main material position of the tower Segment 4 and 5, which is consistent with the phenomenon in
the linear buckling analysis. The reason for the failure of the tower is that the cross section of the main material in these two segments is small, while the wind load of the lines is large. Under the lateral force, the main material of the pressurized side is instability because of the larger axial force.

4. Dynamic analysis of transmission tower line system

The transmission tower line system model is established by combining ABAQUS/CAE with Input file command flow. Among them, the middle tower is the target tower. The dynamic characteristics of single tower and tower line system are compared and analyzed. After that, the wind load time history of the structure is generated, the dynamic response of the structure under wind load is calculated using Dynamic/Implicit and the ultimate wind resistance capacity of the transmission tower line system is studied.

4.1. Modal analysis of single tower

The modal analysis of the tower was carried out in the ABAQUS, and the first to tenth vibration mode were obtained, as shown in table 3. The first to fourth order vibration modes are shown in figure 5.

| Mode | Frequency (Hz) | Mode shapes |
|------|----------------|-------------|
| 1    | 2.3486         | Flat motion in vertical direction (X) |
| 2    | 2.6638         | Flat motion along the transmission line (Y) |
| 3    | 2.9094         | Global torsional mode around the Z axis |
| 4    | 5.2620         | Local mode of two segment between the bottom two cross section |
| 5    | 6.8248         | Local mode, the occurrence position is the same as mode 4 and form is different |
| 6    | 6.8433         | Local mode, the occurrence position is the same as mode 4 and form is different |
| 7    | 7.5980         | Local mode, the occurrence position is the same as mode 4 and form is different |
| 8    | 8.5762         | Flat motion along X direction and local mode |
| 9    | 8.8636         | Flat motion along Y direction and local mode |
| 10   | 8.8703         | Local mode, the occurrence position is the same as mode 4 and form is different |

(a) first-order vibration mode (b) second-order vibration mode
4.2. Wind load simulation of transmission tower line system

The wind field simulation of transmission tower line system is divided into two steps. First, the average wind speed of each point of the structure is generated, and then the fluctuating wind speed time history is simulated. The total wind speed time history of each point can be obtained by superposition of the two points[12-13]. The wind field is simulate using MATLAB. The basic wind speed is 41.5 m/s and the wind speed time history at the height of 10m is shown in figure 6.

![Wind speed time history at the height of 10m](image)

4.3. Modal analysis of transmission tower line system

The first 400 order vibration modes and frequencies of transmission tower line system are obtained using the Lanczos algorithm. And the first 228 order is the vibration of the lines, and the 229 vibration mode is the vibration of the tower in the vertical direction (frequency is 1.71 Hz) as shown in figure 7. The 245 vibration mode is the torsional mode of the tower (frequency is 1.80 Hz) as shown in figure 8. Note that, there is no local vibration in the first 400 vibration modes.
4.4 Dynamic Analysis of transmission tower line system

Before dynamic analysis, the weak members of the tower have been evaluated based on the failure state and the critical wind speed given by the static analysis. Considering the stability of the compression element, the strength of the unstable element in the static analysis is reduced in the dynamic calculation model, that is, the stability of these elements is considered in the dynamic calculation process by reducing the strength. The stability coefficients of some representativeness members are shown in table 4.

Table 4. Stabilisation Factor

| Location | Type            | Number  | Specifications | Stability coefficient |
|----------|-----------------|---------|----------------|-----------------------|
| Segment 4| Main element    | 401/403 | L125×10        | 0.891                 |
| Segment 5| Main element    | 501/507 | L125×10        | 0.861                 |
| Segment 6| Main element    | 601/602 | L160×12        | 0.769                 |
| Segment 6| Oblique element | 607/608 | L75×5          | 0.387                 |
| Segment 6| Oblique element | 605/606 | L70×5          | 0.291                 |
| Segment 9| Main element    | 901/902 | L160×16        | 0.802                 |
| Segment 9| Oblique element | 909/910 | L90×7          | 0.197                 |
Based on the reduced model and the generated wind load, the dynamic analysis of the tower line system is carried out using NEWMARK-β method, and the failure of transmission tower line system is obtained, as shown in figure 9.

5. Conclusion
The FE model of single tower and transmission tower line system is established using ABAQUS. The ultimate capacity of transmission tower is studied based on static analysis. In the meantime, the wind load time history of transmission tower system is simulated. Then, the dynamic analysis is conducted to investigate the response of the tower line system. Through this research work, the following conclusions are summarized:

(1) In the linear buckling analysis, the failure positions of the first to sixth modes are all the Segment 4 and 5, which is the weak position of the transmission tower.

(2) In the nonlinear buckling analysis, the stress of the main elements in Segment 4 and 5 of the tower are very large, which is consistent with the results of linear buckling analysis.

(3) The reason for the failure of the tower is that the section of the main elements in Segment 4 and 5 is small, while the wind load of the lines is large. Under the lateral force, the main elements become instable.
(4) The weak position of dynamic analysis failure is basically the same as static analysis and the critical wind speed of dynamic analysis is 41.5 m/s, which is smaller than that of static calculation.

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