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Structural Mechanics Analysis and Safety Assessment of Transmission Tower

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Abstract. The safety of transmission tower structure is an important guarantee for the reliable operation of the transmission and distribution line. Furthermore, the perennial corrosion of steel components greatly weakened its ultimate bearing capacity, which is a huge detriment to the structural safety. Based on Analytic Hierarchy Process, the tower was divided into four layers and the components were classified into three categories. Corrosion allowance was used to define security index so that hierarchical and structural safety could be calculated.

1. Introduction
Transmission tower is mainly composed of carbon steel components. It is exposed to the atmosphere in its entire life cycle. Which will leads to chemical and electrochemical corrosion and damage of structural stability of the tower. Therefore, it is of great significance to propose an effective method to carry out the security assessment of existing tower based on corrosion status.

A simulation model based on corrosion status of existing towers is established by Chen Lu and Xu Shanhua [1], also a tower safety rating method based on reliability criteria is proposed; Based on the durability evaluation of corroded angle steels, Qian tin, Liang Hao [2] put forward a health scoring method for different components; Based on the material tensile test of corroded components, Cui Xiangyang and Hao Lanrong [3] established the material degradation model for calculating the residual bearing capacity of angle steels, and proposed the classification and maintenance methods of the components; Sun Dengkun [4] evaluates its safety status by the change of the nodal displacements of the tower finite element model. Through the analysis, it is found that the effect of stress concentration caused by local corrosion on the strength of steels has not been considered in the present study. The main limitation is that only the safety of single or several components is evaluated, and the safety assessment of the whole structure system is not carried out.

In view of this, considering the structural characteristics of tower, a method for evaluating the safety degree of tower structure system is proposed. The structure is layered according to the layout. Components of each layer are classified according to the stress characteristics and importance. Then the safety index of each basic component is calculated and the security index of layers and the whole structure are obtained according to the proposed algorithm.
2. Structural finite element model and component safety index

2.1. Establishment of FEM model
ANSYS finite element analysis software 14.5 is used to establish the truss-beam hybrid unit model of transmission tower. The beam element is used (beam188) to simulate main members that is subjected to axial tension and compression, and also subjected to bending moment and shear force. The truss unit (link180) is used to simulate the oblique and auxiliary members that just bear axial force. Section and material properties of angle steel members are defined according to construction drawings. The whole degrees of freedom of the four nodes are restricted at the contact points between the tower legs and the foundation. The ice weight and wind loads of the transmission lines and earth wires are calculated according to the method provided in manual [5], and the wind loads of the tower is segmented according to the variation of wind load coefficient along the height. The tower structure is shown in Fig.1.

![Fig 1. Finite element model of the transmission tower](image)

2.2. Component safety index
The safety index of components is defined by its corrosion tolerance, the corrosion allowance of the component under the limit condition can be expressed as:

\[ e = \frac{\eta_m - \eta_c}{\eta_m} \]  

\( \eta_c \) —loss ratio of cross section of components; \( \eta_m \) —the critical loss ratio of components, section loss due to the allowable stress of the component under the limit load condition.

The calculation of critical section loss rate should consider the variation of component stress and material yield strength with section loss. The reduction of the angle steel leads to the increase of the displacement of the tower structure and the redistribution of the internal force of the components. Therefore, the component stress is not linear with the section loss rate. It should be obtained from the finite element model in which the corrosion rate is parameterized. Increase of the corrosion of the components leads to the uneven loss of the cross section of the angle steel and the stress concentration on the surface. And the yield strength of the steel component decreases accordingly [6]. Jiang Lianjie Chang Mingfeng [7] obtained the nominal yield strength expression of steel components by material tension test.
\[ f_r = (0.986 - 1.083\eta)f_d \]  

(2)

\(f_r\) — nominal yield strength of corroded angle steel; \(f_d\) — Yield strength of non corrosive angle steel; \(\eta\) — Section loss ratio of angle steel.

The stress distribution of ZM4 transmission line on 10KV transmission line under the limit condition whose cross section loss ratio are 0, 2%, 5%, 8%, 10%, 13%, 15%, 18%, 20%, 30% and 50% is calculated with the finite element model. For a calculation example, extract the stress of different sections of main members in tower body 2, and the curve representing the relationship between section loss ratio and stress is fitted in MATLAB, and the curve represented by formula 2 is drawn under the same coordinate axis, as shown in figure 2.

In Fig. 2, the abscissa value of the intersection of two curves is the critical cross section loss ratio of 18.5%. The left side of the point indicates that the yield strength of the material is higher than the stress of angle steel, and the component has a certain strength reserve; the right side indicates that the stress of the angle steel is greater than the yield strength, and the component yield failure.

Thus, the physical meaning of corrosion margin \(e\) can be obtained: when \(e< 0\), the corrosion ratio of components is greater than allowable value, and the components fail; when \(0< e< 1\), the corrosion ratio of components is less than allowable value, and the value of \(E\) can quantify the corrosion degree of the components.

3. Overall structural safety analysis and evaluation

3.1. Stress characteristic of tower structure

The vertical loads of transmission tower are mainly the gravity and ice loads of the tower and wires, and the transverse loads are mainly the wind loads of tower and frozen wires. Loads and arrangement of the components are symmetrical. Force transmission characteristics and load conditions of the same type of components are similar. Meanwhile, same component type and connection mode are found in the same height section, and the stratification is obvious along the height direction.

3.2. Component classification and layer structure division

According to the stress characteristics and the importance of the structure, the angle steel components in the tower structure are classified as:
Components I  Main members that play the major supporting role and they are the most important component in structure.

Components II  Oblique members that withstand axial force only and they are important components restricting the degree of freedom and maintaining structural stability.

Components III  Auxiliary members that withstand minor internal forces and they play the minimal role in the components.

The whole tower structure from top to bottom in accordance with the layout features is divided into 4 layers: tower leg, tower body 1, body 2 (just composed by main and diagonal members), tower head. Fig. 3 is the schematic diagram of the tower structure system.

![Schematic diagram of hierarchical structure system](image)

**Fig 3.** Schematic diagram of hierarchical structure system

### 3.3. Layer structure safety assessment

#### 3.3.1. Security index of different types of components

Components I are very important in the structure, and their failure would lead to local instability and chain failure of other components, so the safety index of this kind of components is controlled by minimum extreme value.

\[
e_{i} = \min\{e_{ij}\} \quad , i = 1, 2, \ldots, n_{1}
\]

\(e_{ij}\) — safety degree of the \(i\) Component I in this layer; \(n_{1}\) — the total number of Components I of this layer.

The safety index of components II is calculated by the self weighted average method.

\[
e_{2i} = \sum_{j=1}^{n_{2}} (T_{2j}e_{2j}) \\
T_{2i} = \frac{1 - V_{2i}}{\sum_{j=1}^{n_{2}} (1 - V_{2j})} \\
V_{2i} = \frac{e_{2i}}{\sum_{j=1}^{n_{2}} e_{2j}}
\]

\(e_{2i}\) — safety degree of the \(i\) Component II in this layer; \(n_{2}\) — the total number of Components II of this layer.
The role of components III are less important in the structural system.

\[ e_3 = \sum_{i=1}^{n} \frac{e_{3i}}{n_3} \]  

\( e_{3i} \) — safety degree of the i Component III in this layer; \( n_3 \) — the total number of Components III of this layer.

3.3.2. Safety index of layer structure. The safety index of the layer structure should consider the safety degree of each kind of component and its contribution weight in this layer. Therefore, the weighted average number of all kinds of components is used to calculate the safety index of layer structure i.

\[ E_i = \sum_{j=1}^{3} w_j e_{ij} \quad i = 1, 2, 3, 4 \]  

\( w_j \) — the weight of the security of components j in the i layer; \( e_{ij} \) — the security index of components j in the i layer.

3.4. Overall safety assessment
The tower structure is composed of the simplified layer structure in series, and the failure of each layer would lead to the instability of the system. According to this property, the comprehensive safety index is calculated by the extreme value method.

\[ E = \min\{E_i\} \quad i = 1, 2, 3, 4 \]  

\( E_i \) — safety index of the i layer structure.

4. Analysis of project example
Taking the 110KV cathead tower Zm4 of Central China Power Grid as an example, in where the maximum wind speed is 30m/s and the ice thickness is 0mm.

By consulting the data of local humid time, sulfur compounds and salt pollutants in the air, the atmospheric corrosivity grade of the service area was C3 according to the national standard [8-9]. In this corrosive environment, the corrosion rate of carbon steel in the first year was 25-50μm/a, and the corrosion rate was 5-12μm/a in the first ten years. After ten years exposure, the corrosion rate was 1.5-6μm/a. The safety condition of the tower after 15 years of service is calculated, and the safety index of all kinds of components and layer structure is shown in table 1.

| Layer         | Components I | Components II | Components III | Safety index of layer |
|---------------|--------------|---------------|----------------|-----------------------|
| Tower head    | 0.5714       | 0.5061        | 0.7249         | 0.5609                |
| Tower body 1  | 0.5971       | 0.5971        | 1.0000         | 0.6668                |
| Tower body 2  | 0.6007       | 0.6523        | 0.7893         | 0.6311                |
| Tower leg     | 0.4397       | 0.5264        | 0.6448         | 0.4846                |

The results show that the tower is in a safe state after 15 years of service, and 48.46% of the corrosion tolerance remains. Components I in the tower leg (main and diagonal members) and
Components II in the tower head (diagonal members) is relatively low, and should be paid more attention to in the maintenance and overhaul.

5. Conclusion
A simplified method for evaluating the safety of corrosion-damaged transmission tower structure is established in this paper, which not only considers the safety status of a single component but also analyzes the whole structural safety index hierarchically according to the connection form of components and the contribution to structural safety. This assessment method also has the following significance:

(1) The safety index of each component and each layer structure is calculated respectively. Which quantitatively characterizes the weak links in the structure and provides reference for the maintenance and overhaul of the transmission tower;

(2) Once the corrosion environment and corrosion characteristic parameters of the tower service site are obtained, the calculation model proposed can predict the safety decline trend of the components and the layer structures, and identify the components and layers that have reached the dangerous state earlier.

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