Analyzing the Limit Loading of Transmission Tower by Means of Finite Element Model

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Abstract. The truss structure has been widely used in the area of high-voltage electric power transmission due to its limited mass and great stiffness. The carrying capacity should be known in advance before the practical usage of transmission tower. As a result, analyzing the limit loading of transmission tower can be significantly useful. In this research, a model of transmission tower structure has been established by a software named Abaqus 6.14. By imposing different loading forces to the finite element model, the locations of limit stress and displacement were figured out. It has shown that the truss structure in this article can bear no more than 198 kN of loading. Stresses meanly distribute in the two side of the tower body, decreasing with the increasing height. The limit stress shows up at the bottom and is at same side of loading force. Stress and displacement responses fit Hooke’s law perfectly, in other words, the proposed finite element model can be used in the design of transmission tower in practice.

1. Introduction
High-voltage electric power transmission (HVEPT) is a way of electrical energy redistribution. It is very important for human life since almost every daily thing is related to electric, we cannot live without it. For this reason, the project of HVEPT can be significantly meaningful, including its security and reliability. One of the most important parts of HVEPT is transmission tower, which is normally built with truss structure. While this structure is working, it has to endure huge electrical impact from power transmission lines (PTLs), in order to ensure that the transmission tower can work successfully and will not be broken by the impact of PTLs or any other influence (like earthquake), we have to calculate and evaluate the limit loading of transmission tower. Due to the importance and non-displaceable use of transmission tower, heaps of research have been taken for several decades. Knight and Santhakumar [1] conducted tests on a full-scale quadrant of the lowest panel of a transmission tower. This research indicates that even under normal working-load conditions, the secondary stresses caused by bolted joint could be significant enough to cause failure of leg members. Itam et al. [2] studied the joint with the maximum stress by using STAAD Pro software; they pointed out that the stress produced during the analysis of structure will be dramatically higher if the joint detailing is considered, which means that the joints and connection play an important role in distributing stress. Kang and Zhang [3] analyzed the dynamic response of the transmission tower based on finite element method, using ANSYS Workbench. By analyzing the seismic response spectrum, the research turned out that the highest stress will be produced at the bottom of tower in a vibration situation. And in order to improve the quality of the design and shorten the design cycle, Xu et al.[4] gave a model of overhead transmission line-towers system by using parameterized finite element method. In order to reverse engineering and structural analysis of electricity transmission tower structures, Conde et al.[5] have also presented a multidisciplinary approach which is a mixture of laser scanning systems and finite element method,
making it possible to analyze the effect of internal structural imperfection. Researches above are significantly helpful to the construction of transmission tower, especially in China, a country of mountain with much need of electricity. During the usage of truss structure, the loading forces affect the stability of the transmission tower [6,7], and lead to the failure [8,9]. And in this paper, in order to demonstrate the accuracy of the means of finite element model (FEM), the FEM will be established by Abaqus, and by imposing different loading forces, the different responses of the limit stress and displacement will obtained. Based on the results, the consequences fit the reality perfectly and the means of FEM is extremely useful in the analysis of transmission tower.

2. Finite Element Model
The purpose of this part is to describe details of this finite element model. Abaqus 6.14-4 has been used to establish the truss model, and dimensions of this model has been shown in the Fig. 1a (with unit meter). As shown in Fig. 1a, the tower is 100 m high and 20 m wide at the highest and lowest part. All the truss in this tower is a kind of pipe with diameter 100 mm and 10 mm thick. After that, the tower model is totally symmetrical except the position of loading, and it has two roller supports at the bottom(see Fig. 1b) as boundary conditions, limiting the displacement of director x and y. At the left head of this tower, different loading (concentrated force) will be added to simulate the real working condition (see Fig. 1b), like the impact of PTLs. Steel is the material of this tower, the mass density is 7800 kg/m3, Young’s modulus is 210 GPa, possion’s ratio is 0.3, the maximum stress this material can bear is 345 MPa. There are 4778 nodes and 4844 elements in this model, all the linear line elements are in the type of B31. The loading force is located at node No.4506. In this research, all the conditions above are fixed except loading value. The purpose is to find out the limit loading through increasing the force until that the maximum stress of this tower is 345 MPa. And we can see the job list at Table 1. The minimum force is 1 kN while the maximum is 200 kN.

![Figure 1](image_url)

**Figure 1.** (a) The characteristic length of the transmission tower; (b) Finite element model for the mechanical analysis of transmission tower.

| No. of FEM | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
|------------|----|----|----|----|----|----|----|----|----|----|----|
| Loading force (kN) | 1  | 2  | 4  | 6  | 8  | 10 | 15 | 20 | 50 | 100| 200|

**Table 1.** Different loading forces for FEM.
3. Mechanical Response

3.1. Stress Response

Through the result, all the stress cloud charts possess the same distribution of stress, so we can just take the chart of 200 kN for example (See Fig. 2). In this cloud chart, we can find out that the maximum stress is 347.9 MPa, located at the left bottom of the tower (node No.33), Fig. 2 has shown the information of this node. And the minimum is approximately 2.714e-4 MPa, located at node No.3424. After that, we can also see most stress distribute at the two sides of the tower body, as the altitude lower, the stress will become higher. In the truss where the node No.4506 (location of loading force) belongs shows the stress concentration, the stress there is approximately 71.4MPa~72.0MPa. At other parts of this model, like the across trusses in the middle of tower body, stress is almost 0, which can be ignored in most engineering situations. Fig. 3 has shown the stress response to different loading forces. In this chart, linearity is obvious, which is identical to the law of Hooke. If we, however, take 200 kN as the maximum loading force, the limit stress is 347.9 MPa which is bigger than the allowable stress of steel (345 MPa).

![Figure 2. Stress distribution and output from the simulated results.](image)

![Figure 3. Relationship between loading force and stress.](image)
3.2. Displacement Response
As to the displacement responding, they also have the same distribution like stress responding, so we just take the 200 kN for example (See Fig. 4). Through this cloud chart, we can notice that the maximum displacement is 855.6 mm (in the figure it is the minimum, because of direction). And it is located where the input force is. And the direction of displacement is the same with loading force direction; the displacement diminishes as the altitude becomes lower. In the Fig. 5, the connection of maximum displacement and loading force has been shown. As we can see clearly, the Max displacement increase linearly as the loading force increasing, just like stress responding, it fits the law of Hooke.

![Figure 4. Displacement distribution in FEM result.](image)

![Figure 5. Relationship between loading force and maximum displacement.](image)

3.3. The Ultimate Loading Force
Because of the linear phenomenon, 198 kN has been put into simulation, and the result (See Fig. 6a) is perfect, the maximum stress is 344.4 MPa. In other words, this transmission tower will be broken and failure when the loading force is larger than 198 kN. Like the part of stress analyzing, we must see how the tower displacement responses when the loading force is 198 kN. Fig. 6b is the cloud chart of that situation. The maximum displacement is 847 mm, which means the position of loading will move with 847 mm through the loading force while the tower is failure.
4. Conclusion
In this paper, based on the FEM of truss structure established by Abaqus 6.14, as the analyzing conducted, it comes with these conclusions:
(1) The ultimate loading force and the corresponding displacement of the transmission tower are respectively 198 kN and 847 mm.
(2) The limit stress and displacement show linearity while increasing the loading force, fitting Hooke’s law perfectly.
(3) The linear relationships are in agreement with the elastic theory, implying that the proposed finite element model is valid to analyze the mechanical properties of transmission tower.

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