The effect of the thickness of steel pipe in linear and 2-dimensional stiffness analysis during design of transmission tower

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Abstract. Transmission towers are truss structures which are used to support the transmission power lines. It is important to design the transmission towers because unsuitable dimensions could waste the steel or lead to the failure of transmission towers. The thickness of the beam is a critical parameter during the design of transmission tower, which is directly related with the safety of the transmission tower. In this paper, a finite element method in linear and 2-dimension was employed to simulate the mechanical behaviour of transmission tower. Based on the calculated results, the variations of the maximum stress and the maximum displacement with the increasing thickness were displayed. Both the stress and displacement decrease dramatically with the increasing thickness and reach to a stable value if the thickness is beyond a critical thickness. When the thickness changes from 1 mm to 4 mm, the maximum stress and the maximum displacement decrease by 74%. When the thickness is more than 4 mm, the reduction of stress and displacement is not obvious. The percentage reduction of more than 70% is determined to be the criterion for optimum thickness. The relationships can be used in the design of the transmission tower.

1. Introduction

The mechanical properties of transmission towers have been researched from last century. Ultimate loading is an important parameter related with the safety of transmission tower [1]. The ultimate loading can be obtained by measuring the stress of transmission tower during experiments [2, 3]. The periodic for the design of transmission tower could be longer if the experiment is only used. With the development of finite element software, the ultimate load and mechanical responses can be predicted by finite element analysis [4-6]. Based on the numerical results, the design of transmission towers can be modified to improve the safety [7]. The effect of the geometry on the strength of transmission towers was studied by a large scale simulation [8]. Numerical results revealed the limitation of the height of transmission towers [9]. The stress distribution and initial stress were calculated by finite element model [10, 11]. Recently, the numerical models for transmission tower could be quickly carried out by Solidworks, Workbench ANSYS and ABAQUS [12, 13]. Moreover, based on the numerical results in finite element software, Borja et al. optimized the transmission tower by the stress distribution within the transmission tower [14]. The previous works concentrate on the effect of height, loading force, stiffness and wind loading on the mechanical responses of transmission tower. Though the beam thickness of transmission power is related with the stiffness, the sole effect of beam thickness on the mechanical responses of transmission tower has not been investigated. The thickness
of beam is a critical parameter during the design of transmission tower, which is directly related with the safety of the transmission tower. The optimum thickness can save the usage of steel and ensure the enough stiffness; therefore, it is needed to research the mechanical responses of transmission tower at a range of beam thickness. Here, commercial finite element software (ABAQUS 6.14-4) was employed to analyze this variation. The relationships between the thickness and mechanical response were given out for the design of the transmission tower.

2. Finite element model

2.1. Geometric model
Power transmission tower is mainly composed of truss structures, and also the truss structure is the major stress component of power transmission tower. The power transmission tower model was built directly in the Abaqus, which is 100m in height, 20m in width at the bottom, 8m in width at the top, and with three pairs of wings as shown in Figure 1. The whole truss structure consists of pipe with radius of 0.05m and thickness varying from 1 mm to 10 mm. The truss is connected to the ground by two hinged joints on the bottom of the truss. Then the model is imported into the finite element program and is forced diagonally to the right with a load, which is a concentrated force of 10000N.

2.2. Material model
In the engineering application, the deformation of transmission tower is not allowed to be plastic deformation. Furthermore, the safety factor is considered to make sure the safety of transmission tower. The safety factor is commonly more than one; so that the allowable stress is smaller than the yield strength. When the transmission tower is designed, the stress value is calculated in its elastic range. Therefore, the analysis is linear, 2-dimensional and no failure criteria. The main diagonal material and auxiliary materials of the tower are made of steel with the elasticity modulus of 210GPa, a Poisson's ratio of 0.3 and density of 7800kg/m³.

2.3. Numerical model
The mesh structure is divided into seed parts with an approximate global size of 0.2m. There are 1320 nodes and 1400 linear line elements of type B31 in total. The finite element model for the transmission tower was shown in Figure 2, where the loading force and the boundary conditions were illustrated. The simulation conditions are displayed in Table 1. The thickness of pipe varies from 1 mm to 10 mm and ten simulated cases were carried out here. Because the deformations of tension, compression and bending can be happen, the Mises equivalent stress was chosen to reflect the mechanical response of transmission tower.
Table 1. Structural parameters of pipe for transmission tower.

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Diameter (cm) | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  | 10  |
| Thickness (mm) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |

3. Mechanical response
In engineering practice, it is necessary to study the stress of power transmission tower, that is subjected to different types of forces as wind, snow, rain and so on, and whether the induced stress is relatively well-distributed or not, namely the maximum stress and the distribution of the stress and the displacement of the power transmission tower. Figure 3 shows the stress distribution for the pipe thickness of 5mm. The maximum stress value of power transmission tower is 32.7 MPa which is occurred at the bottom of communication tower. The maximum stress concentrates on the parts where the tower is hinged to the ground. And the stress is maximum at the bottom and becomes smaller at the top part of the tower. On the contrary, as shown in Figure 4, the displacement is smaller when the position is closer to the hinged joints and the maximum appears on the top of the transmission tower. For the pipe thickness of 5mm, the maximum displacement is about 82.3 mm.

![Figure 3. The stress distribution in transmission tower at the pipe thickness of 5mm.](image-url)
Figure 4. The stress distribution in transmission tower at the pipe.

By increasing the thickness of the pipe from 1 mm to 10 mm, the relationship between the thickness and the mechanical responses was obtained. Based on the calculated data, the variations of maximum stress and maximum displacement with the increasing thickness are illustrated in Figure 5. Both the maximum values of the stress and the displacement decrease with the increasing pipe thickness. If the pipe thickness varies from 1 mm to 4 mm, the maximum stress and the maximum displacement dramatically decrease. The maximum stress and the maximum displacement vary slightly with the increasing thickness when the pipe thickness is beyond 4 mm. That is to say, when the pipe thickness is larger than a critical value, there is no need to further increase the pipe thickness. The larger thickness could lead to the waste of steel materials. Based on the standard of DL/T5254-2010, the optimum thickness is 4 mm. When the thickness changes from 1 mm to 3 mm, the maximum stress and the maximum displacement decrease by 66%. When the thickness changes from 1 mm to 4 mm, the maximum stress and the maximum displacement decrease by 74%. When the thickness changes from 1 mm to 5 mm, the maximum stress and the maximum displacement decrease by 79%. According to the optimum thickness of 4 mm in DL/T5254-2010, the percentage reduction of more than 70% is chosen to be criterion for optimum thickness. From the calculated results in Figure 5, the optimal pipe thickness is 4 mm for the design of transmission tower whose dimension parameters are shown in Figure 1.
Figure 5. Variations of maximum stress and displacement with the increasing thickness (a) Variations of maximum stress with the increasing thickness; (b) Variations of maximum displacement with the increasing thickness.

Figure 6. Comparison between the present results and the available standard.
Based on the calculated results, the relationships between mechanical responses and wall thickness were fitted by means of exponential function. Eq. (1) shows the exponential relationship between maximum stress and wall thickness:

\[ \sigma_{\text{max}} = 250 \exp(-0.6t^{0.7}), \]  

where \( \sigma_{\text{max}} \) is the maximum stress and \( t \) is the wall thickness.

The fitting function in Figure 5b is in the following form:

\[ S_{\text{max}} = 600 \exp(-0.6t^{0.7}), \]  

where \( S_{\text{max}} \) is the maximum displacement.

According to Eqs. (1)-(2), the relationships between maximum stress, maximum displacement and wall thickness are exponential. The coefficients in exponential function are different from each other.

Figure 6 shows the comparison between the present results and available design standard. In DL/T 5254-2010, the proposed thickness is 4 mm. If the thickness is less than 4 mm, the designed transmission tower will be in a risk of collapse. Here, we reveal the underlying mechanism on the optimum thickness by conducting a series of numerical calculations. It is illustrated in Figure 6 that the percentage reduction will increase gradually with the increasing thickness if the thickness is beyond 4 mm. The percentage reduction of more than 70% is chosen to be criterion for optimum thickness. The criterion of more than 70% percentage reduction can be used more widely than the available standard because the standard is employed in the special conditions. Moreover, the criterion of more than 70% percentage reduction is more suitable to be implemented into finite element software with the rapid development of commercial finite element method.

4. Concluding remarks
In this paper, a finite element model for the transmission tower was established by means of ABAQUS 6.14-4 software. The pipe thickness varied from 1 mm to 10 mm in the proposed finite element model. Based on the calculated results, the following conclusions are drawn:

1. The relationship between the mechanical responses and the pipe thickness is nonlinear.
2. With the increasing pipe thickness, both the maximum stress and the maximum displacement decrease dramatically for small thickness and then decrease slightly for large thickness.
3. There is an optimal pipe thickness beyond which the thickness has a slight effect on the mechanical responses of the transmission tower.
4. The percentage reduction of more than 70% is chosen to be criterion for optimum thickness. The optimum thickness for transmission tower is 4 mm by employing the proposed criterion.

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