Multi-scale Modelling and Wind-induced Vibration Analysis of Transmission Tower Structure

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Abstract. Based on the theory of node displacement compatibility, the multi-point constraint equations of beam-solid elements are derived. The beam element model and multi-scale model are established to analyze the wind-induced vibration response of the transmission tower. The analysis results demonstrate that the dynamic response of the two models is similar in the elastic stage, but the response of the multi-scale model is larger than that of the beam element model in the plastic stage. The main reason is that the multi-scale model can consider the stiffness degradation and cracking of the angle cleat, which will in turn influence the mechanical performance and failure mode of the structure.

1. Introduction

High voltage transmission tower is widely used and is an important lifeline power engineering facility. It is of great economic and social significance to ensure the safe and reliable running of the main structural system under the condition of a long transmission line, a varied topography and complex loads.

At present, there is little work on multi-scale analysis of transmission tower structure. In order to investigate the influence of the joint rigid zone on the mechanical behaviors of main members in the steel tabular tower, Liu Haifeng et al. [1] derived the constraint equations to connect the micro-scaled model and the macro-scaled model and analyzed 6 towers by multi-scale finite element method. Zhu xiaofei [2] carried out the multi-scale analysis of the joint plate of the transmission tower considering the welding residual stress by establishing a sub model. Wang Fengyang[3] analyzed the collapse of transmission tower structure under downburst, and proposed a multi-scale model correction method based on Kriging method.

The traditional finite element analysis method of transmission tower structure is to establish macro model and micro model respectively to obtain its overall response and analyze local parts, without considering the coupling effect between them, which failed to consider the influence of the node effects on the overall response accurately. The multi-scale modelling technology can solve the problem and reduce the calculation time with good calculating precision by establishing the micro element model of the key parts and the macro element model of the rest part, and connecting them effectively.

In this paper, the multi-point constraint equation of the interface of the beam-solid element is derived by the multi-scale theory based on displacement compatibility, and the application of multi-scale modelling method in the dynamic analysis is studied. The damage process of local members is analyzed by multi-scale modelling, which provides a basis for structural design and reinforcement. The overall response results of the beam element model and the multi-scale model are
compared to study the applicability of the multi-scale modelling technology in the dynamic analysis of transmission tower structures.

2. Derivation of Multi-point Constraint Equation of Beam-solid Element
The multi-point constraint equation can be derived from the displacement compatibility relations of the nodes on the interface between the models of different scales.

![Diagram of beam-solid element connection](image)

The beam-solid element multi-scale model is shown in Figure 1.1. There are n nodes on the interface of the solid element, from S₁ to Sₙ, each node has three degrees of freedom: X, Y, Z, while there is only one node B on the interface of the beam element, and there are six degrees of freedom (X, Y, Z, θₓ, θᵧ and θ ż ). The node of the beam element is connected to the center of the solid element section. According to the displacement compatibility condition, the constraint equations are as follows:

\[
\begin{align*}
    x_i &= x_B + R_{xi} (\cos \theta_{xB} - 1) - R_{yi} \sin \theta_{zB} \\
    y_i &= y_B + R_{yi} (\cos \theta_{xB} - 1) - R_{zi} \sin \theta_{zB} \\
    z_i &= z_B - R_{zi} \sin \theta_{xB} + R_{yi} \sin \theta_{zB}
\end{align*}
\]

(1)

Where \( x_B, y_B, z_B \) are the tangential and axial displacements of the node on the interface of the beam element;

\( \theta_{xB}, \theta_{yB}, \theta_{zB} \) are angular displacements of the node on the interface of the beam element;

\( x_{si}, y_{si}, z_{si} \) are tangent and axial displacements of node Sᵢ on the interface of the solid element.

\( R_{xi}, R_{yi} \) are the coordinate values of node Sᵢ on the interface of the solid element in the x-axis and y-axis.

It should be noted that the equation is based on the assumption of plane section[4] and under the condition that the torsional angle at the interface is relatively small.

3. Computational Evaluation of the Transmission Tower Structure Performance
In this section, considering geometric and material nonlinearity, the multi-scale model of transmission tower structure is established. The dynamic response of transmission tower under wind load is analyzed by the time-history analysis method.

3.1. Multi-scale Model
The object this paper studied is the Z27-21 linear transmission tower[5], which is used for the 800 kV UHVDC transmission project from Yunnan to Guangdong. As shown in Figure 2.1(a), it is the first 800 kV HVDC transmission project in the world, with a total length of about 1417 km. In the model, the coupling effect of wires, ground wires and insulator strings with the transmission tower is ignored,
and the gravity load and wind load are directly applied to the transmission tower structure[6].

3.1.1 Analysis steps. The specific modelling and analysis steps of the multi-scale model are as follows:
(1) Establish a beam element model of the overall structure of the transmission tower, and achieve the dynamic response of the overall structure under wind load.
(2) Find out the key parts which are easy to be damaged and the specific locations of the elastic-plastic deformation boundary according to the results of the beam element model. Establish a solid element model for the key parts, and keep the beam elements unchanged in other regions. At the same time, keep the multi-scale interface consistent with the elastic-plastic boundary.
(3) Establish the multi-scale model by coupling the node of the beam element with the node of the solid element on the interface through the multi-point constraint equation.

3.1.2 Finite element model. The modelling and analysis is based on the ABAQUS platform. B31 is adopted for the beam element, and C3D8R is adopted for the solid element. The overall model is shown in Figure 2.1(a).

Obvious plastic deformation of the main rod on the middle part of the tower can be observed under the wind load at 90° direction. The analysis results are shown in Section 3.2. A solid element model for this part is established, as shown in Figure 2.1.

![Overall model](image1)
![Detailed solid model](image2)
![Detailed model of node](image3)

Figure 2.1 Multi-scale coupled model of beam entity element of transmission tower structure

The multi-scale model is established by using the multi-point constraint equation of the beam-solid element based on displacement coordination.

3.2. Results Analysis of Transmission Tower under Wind Load
Since a few nodes have plastic deformation and the plastic strain is small under the wind load at 0° direction, so this paper will focus on the nonlinear dynamic response of transmission tower under the wind load at 90° direction.

The results of the dynamic analysis of the beam element model show that the displacement of the structure under the wind load at 90° direction increases continuously, until the structure loses its stability. The maximum deformation occurs in the main rod in the middle of the tower, as shown in Figure 2.2 and Figure 2.3. The stress of the main rod gradually reaches its bearing limitation, and the displacement is also increasing, leading to collapsing of the structure finally. According to the local deformation in Figure 2.3, the detailed model of the key parts and the multi-scale model are established as shown in Figure 2.1. According to results of the dynamic time-history analysis of the multi-scale model, the local deformation process of the multi-scale model is shown in Figure 2.4.
Figure 2.2. Overall deformation of transmission tower

Figure 2.3. Local deformation of transmission tower

Figure 2.4. Dynamic deformation process of transmission tower (Unit: mm)

Figure 2.5. Stress change process of main rod (unit: MPa)

Figure 2.6. Equivalent plastic strain change process of main rod
As shown in Figure 2.2 and Figure 2.4, the failure location of the multi-scale model and the beam element model are both in the main compressed rod in the middle of the tower. In the multi-scale model, the stress nephogram and the equivalent plastic strain nephogram of the main rod at different times are shown in Figure 2.5 and Figure 2.6 respectively. The deformation characteristic of the main rod in the multi-scale model is similar to that in the beam element model. Under the continuous wind load, the stress of the main rod soon reaches the yield point, the plastic deformation of the main rod increases gradually, the internal depression becomes more and more obvious, and the displacement of the overall structure also increases. Finally, the main rod reaches the ultimate bearing capacity, and the whole structure loses stability and collapses.

The strain at different points of the angle steel section changes with time as shown in Figure 2.9. The strain at point 1 and 5 far away from the angle steel back increases slowly, while the strain at point 3 at the angle steel back changes greatly. The strain increases slowly with the wind load at an earlier stage. When the strain exceeds the yield strain, the strain at point 3 increases faster and faster with time, and the section gradually reaches the bearing capacity limitation.
Figure 2.9. Strain-time curve of angle steel section

Figure 2.10. displacement-time curve of vertex

The vertex displacement-time curves of the two models are as shown in Figure 2.10. At the beginning, the displacement response of the whole structure increases continuously, and severe plastic deformation will occur in 0.5 second. When the displacement is less than 400mm, The displacement responses of the two models agree with each other well, indicating that they have the same stiffness in the elastic stage. When the displacement exceeds 400mm, the vertex displacement of the multi-scale model is larger than that of the beam element model, and the displacement response of the multi-scale model becomes greater than that of the beam element model. The bearing capacity of the multi-scale model will be lower than that of the beam element model. The main reason is that the multi-scale model can consider the stiffness degradation and cracking of the angle cleat, which will in turn influence the mechanical performance and failure mode of the structure.

4. Conclusion
The study on the constraint equations of the beam-solid element has been carried out in this paper, and the steps of modelling for multi-scale numerical analyses of transmission towers are studied. The simulation of the Z27-21 transmission tower under wind load was performed. Based on the results of this study, the following specific conclusions can be obtained:

(1) Multi-scale modelling of transmission tower structure can be realized by establishing a solid element model for the local components with plastic deformation, and macro beam element model for the rest components, and then using the method of multi-point constraint equation to realize the connection of the two types of models.

(2) By comparing the multi-scale model and the beam element model, the results show that the two models are similar in the elastic stage, which indicates that the multi-scale modelling technology can be applied to the wind resistance analysis of the transmission tower structure.

(3) Compared with the traditional finite element analysis of transmission tower, the multi-scale model can consider the stiffness degradation and cracking of the angle cleat, therefore, more accurate results are obtained in the calculation of nonlinear dynamic response. In addition, The damage process of local members can be analyzed by multi-scale modelling, which provides a basis for structural design and reinforcement.

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6. References
[1] Liu H F, Yang J B and Han J K 2012 Influence of joint rigid zone on mechanical behaviors of main members in steel tabular tower Spec Struct 29: 29-32.
[2] Zhu X F 2010 The multi-scale research for stress field of transmission towers gusset plate
considering welding residual stress (Wuhan: Wuhan University of Science and Technology) pp 28-55.

[3] Wang F Y 2015 Multi-scale simulation method and collapse analysis of transmission tower structures (Harbin: Harbin Institute of Technology) pp 19-85.

[4] Zhang Y, Sun G and Li H 2015 Interface connection method of multi-scale modelling of concrete structure J Southeast U: Nat Sci Ed 45: 126-32

[5] Zheng C L 2013 Nonlinear analysis of transmission tower based on full scale testing (Wuhan: Huazhong University of Science and Technology) pp 28-39

[6] DL/T 5154-2012 2012 Technical Code for The Design of Tower and rod Structures of Overhead Transmission Line (Beijing: China Planning Press)