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Research on Reinforcement of Connection Nodes of Transmission Line Towers

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Abstract:
The existing research on the reinforcement of transmission lines focuses on the main materials and foundations. To address the key issue of reinforcing the connection nodes between the upper structure and foundation of transmission line towers, a finite element model of this node was established using Abaqus, considering different stress conditions under natural disasters. Comparisons with the calculation results of both original and current specifications revealed that after reinforcing the upper structure, the weakest point is the shear failure of the connecting bolts between the shoe plate and the main material of the node, necessitating an increase in overall load-bearing capacity. Therefore, a node reinforcement plan compatible with the reinforcement type of the upper structure main material was proposed, which allows for construction without power outage and was verified through true type tests. This research on node reinforcement contributes to improving the service value of transmission lines and provides new insights for the reinforcement of similar prefabricated building nodes.

Keywords: transmission line, tower, connection nodes, reinforcement.

INTRODUCTION

Due to the low design standards of transmission line towers that were put into operation in the early days, their disaster resistance ability is difficult to meet the requirements of reliable operation as they enter service. If a new tower is to be built, it not only requires power outage construction, but also involves land compensation, making the implementation difficult and costly. For transmission towers that have not suffered permanent damage, it is worth using repair and reinforcement methods to appropriately reinforce the tower and improve the transmission line's ability to withstand natural disasters.

Transmission line towers can be divided into upper structures, connecting nodes, and foundations, which belong to typical prefabricated steel structures. Currently, there are many studies on steel structure reinforcement technology [1,2]. However, the materials, structures, load conditions, and foundation forms of transmission towers are very different from those of ordinary buildings, especially when reinforcing transmission towers, the normal operation of transmission lines often needs to be considered, which increases the difficulty of reinforcement.

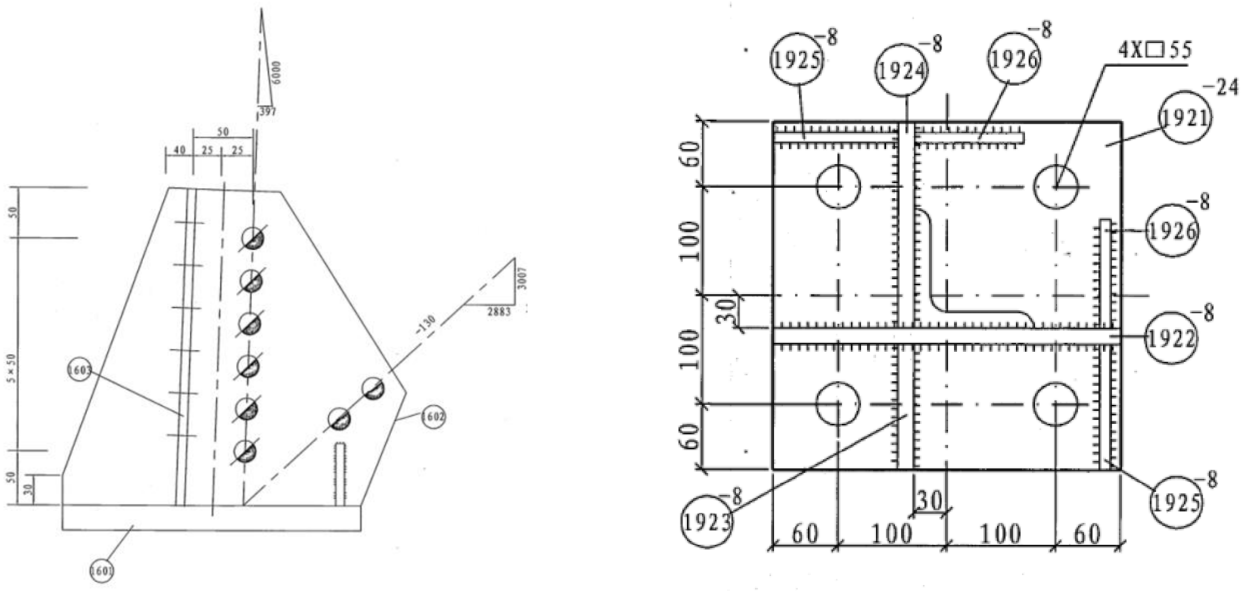
At present, experts at home and abroad have conducted some theoretical and experimental research on the reinforcement of the upper structure and foundation of transmission towers. He Rongbu et al. [3] proposed using unequal angle steel in parallel on the outer side of the main steel to reinforce transmission towers; Szafran et al. [4] studied the weakest part of the iron tower body under different ice cover thicknesses and wind speeds; Liu Xuewu et al. [5] compared the reinforcement effects of cross shaped, Z-shaped, and T-shaped section main steel on transmission line towers; Albermani et al. [6] conducted experimental research and finite element analysis on the local structure of the tower after adding transverse partitions to the tower body; Wen Yi et al. [7] studied the relationship between axial stress and node displacement before and after the reinforcement of the iron tower body; Dong Yiyi et al. [8] developed a new type of fixture that tightly connects reinforced angle steel with the main material angle steel to form a T-shaped composite section component; Zhang Yujin [9] studied the reinforcement methods of replacing main materials, adding secondary main materials, and adding auxiliary materials for transmission towers. The selection of transmission lines needs to avoid various sensitive factors such as planning areas and residential gathering areas, with multiple points and wide coverage [10], resulting in a variety of geological conditions and foundation types for tower structures, and corresponding foundation reinforcement methods [11,12].

The existing research on strengthening transmission towers focuses on the main materials and foundations, and there is relatively little research on strengthening the connection nodes between the upper structure and foundation of transmission towers that bear critical loads (hereinafter referred to as "connection nodes"). The current specifications only simplify the calculation of the bottom plate of the node, and its overall bearing capacity margin is not clear. Therefore, this article selects the early put into operation ZGU1 type tangent tower as the research object, analyzes the overall bearing capacity and deformation degree of the connecting nodes, and proposes a safe, reliable, and economically feasible node reinforcement scheme under the premise of uninterrupted construction.

FINITE ELEMENT ANALYSIS OF CONNECTION NODES

Model Dimension Selection

According to the construction drawing of the ZGU1 type tangent tower, the actual dimensions of the connection nodes are shown in Figure 1(a) and Figure 1(b). The detailed dimensions of specific components are listed in Table 1. The anchor bolts is M42, while the other connecting bolts are of grade 6.8 M16, with all materials being Q235 steel.



(a) Elevation drawing of the node (b) Plan view of the node

Figure 1. Dimension drawing of the connection node

Table 1. Component detail

Number	Specification(mm×mm)	Length(mm)	Quantity	Weight(kg)	
				Per Unit	Subtotal
1921	-24×320	320	4	19.29	77.16
1922	-8×390	356	4	3.09	12.36
1923	-8×138	356	4	3.09	12.36
1924	-8×261	353	4	5.79	23.16
1925	-8×60	116	8	0.44	3.52
1926	-8×60	100	8	0.38	3.04

Element Type

ABAQUS includes mostly structural elements, such as rod elements, beam elements, pipe elements, shell elements, solid elements, etc. Different elements can be selected according to different analysis purposes and requirements. In this study, SHELL and SOLID elements were chosen for the connection node model. Considering the actual shape of the components and the convenience of modeling, this paper adopts solid elements for modeling and analysis.

Material Properties and Model Assembly

The stress-strain curve (σ - ε curve) obtained from the tensile test of steel is usually not precisely input in ABAQUS but replaced by a simplified model. Given that the components involved in this paper are subjected to static and monotonic loading, a bilinear isotropic hardening model was chosen[13]. The slope of the hardening phase is 0.03E. Considering that the main angle steel has been reinforced and treated as a rigid body, the connecting bolts of grade 6.8 were used, with a tensile strength of 600MPa and yield strength of 480MPa. Other steel grades are Q235, with an elastic modulus E of 200GPa, yield strength fy of 235MPa, and Poisson's ratio of 0.3., as shown in Figure 2. The unit network division adopts the sweeping division bolt model and the node overall model as shown in Figure 3(a) and Figure 3(b).

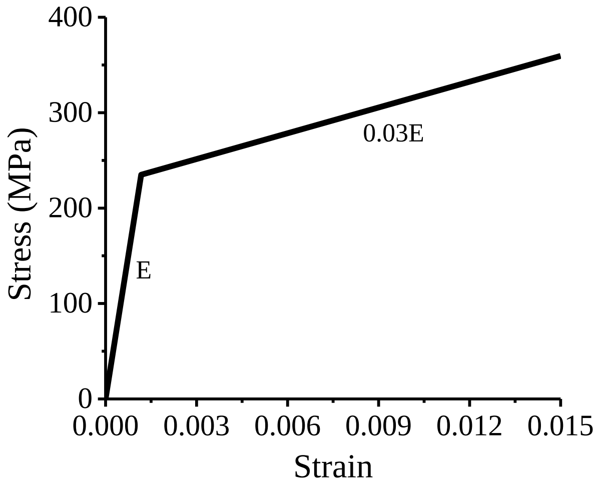
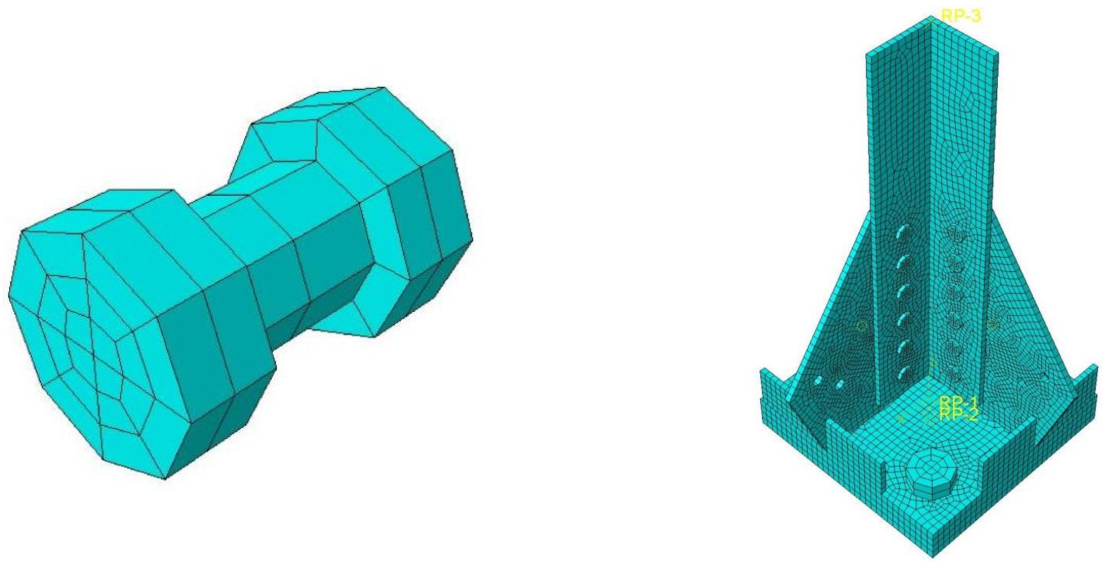


Figure 2. Constitutive Model



(a)Bolt Model (b)Node integrated model

Figure 3. Finite element integrated model of node

Contact, Boundary Conditions, and Analysis Step Settings

In this paper, contact connections were adopted between the main angle steel, bolts, stiffening plates, and shoe plates, with a tangential friction coefficient of 0.2 and normal hard contact[14]. The connection between the base plate and the shoe plate was bound, and the connection between the base plate and the foundation was set as a fixed end. The effects of welding quality and residual welding stress on the connection of stiffening ribs were ignored during finite element analysis[15,16]. Since the analysis of this project model belongs to quasi-static problems, explicit dynamics was used for analysis. Therefore, the simulation process of this paper is divided into two stages: initial stress balance and explicit dynamic analysis, with the frequency set to 50.

Load Calculation and Loading Setup

According to the original design specifications, for the operating transmission tower, the installation condition can be disregarded. The force calculation for various working conditions is listed in Table 2, with the support direction in the X, Y, and Z directions as shown in Figure 4.

Based on the calculation, the most unfavorable foundation action forces for each working condition are X = 47.1 kN, Y = 50.22 kN, Z = 502.33 kN, and the uplift force on the main angle steel is 550.68 kN. According to the actual force situation, the type of amplitude is set as "smooth analysis step."

Table 2. Working condition combinations and force calculation

Working Condition Number and Name	X-direction(kN)	Y-direction(kN)	Z-direction(kN)
1.Strong Wind 90	25.71	43.62	389.34
2.Strong Wind 60	47.1	47.62	502.33
3.Strong Wind 45	1.84	1.84	28.71
4.Strong Wind 0	5.71	10.82	114.61
5.Low Temperature	9.25	7.49	118.21
6.Left Upper and Left Middle Conductor Cut	5.42	10.83	110.68
7.Left Upper and Left Lower Conductor Cut	8.97	7.51	114.29
8.Left Upper and Right Upper Conductor Cut	8.95	7.49	114.09
9.Left Upper and Right Middle Conductor Cut	8.97	7	106.62
10.Left Upper and Right Lower Conductor Cut	12.23	4.19	113.98
11.Left Middle and Left Lower Conductor Cut	3.75	6.56	75.1
12.Left Middle and Right Upper Conductor Cut	6.9	4.59	85.42
13.Left Middle and Right Middle Conductor Cut	42.41	50.22	498.93
14.Left Middle and Right Lower Conductor Cut	37.28	20.53	311.12
15.Left Lower and Right Upper Conductor Cut	5.44	11.36	118.55
16.Left Lower and Right Middle Conductor Cut	8.97	8.01	121.96
17.Left Lower and Right Lower Conductor Cut	8.99	7.52	114.49
18.Right Upper and Right Middle Conductor Cut	8.69	8.03	118.04
19.Right Upper and Right Lower Conductor Cut	8.7	7.54	110.57
20.Right Middle and Right Lower Conductor Cut	9.23	6.97	110.34
21.Left Ground Wire, Left Upper Conductor Cut	12.49	4.16	117.7
22.Left Ground Wire	12.51	3.67	110.23
23.Right Ground Wire	4.91	6.63	85.77

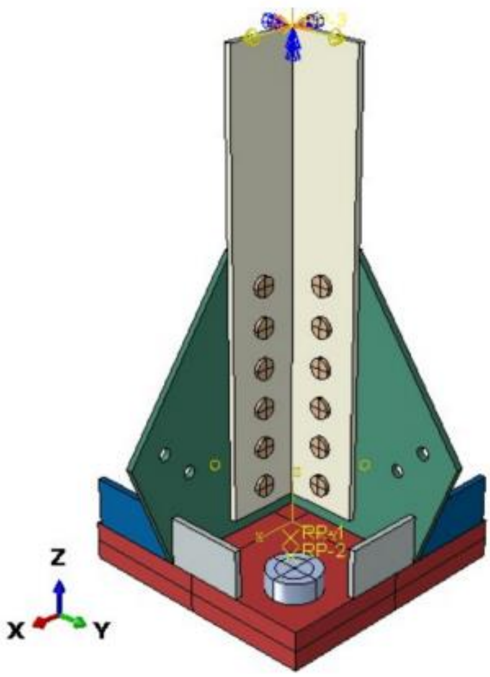
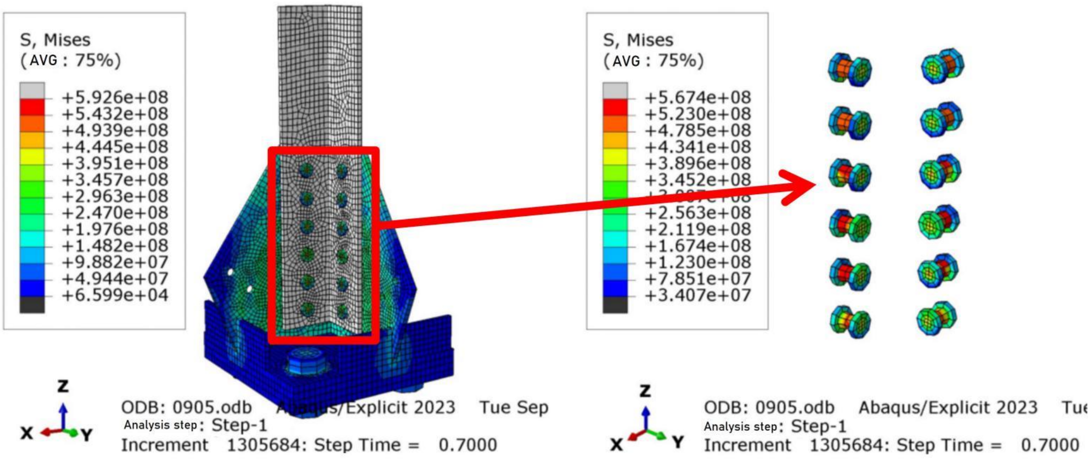


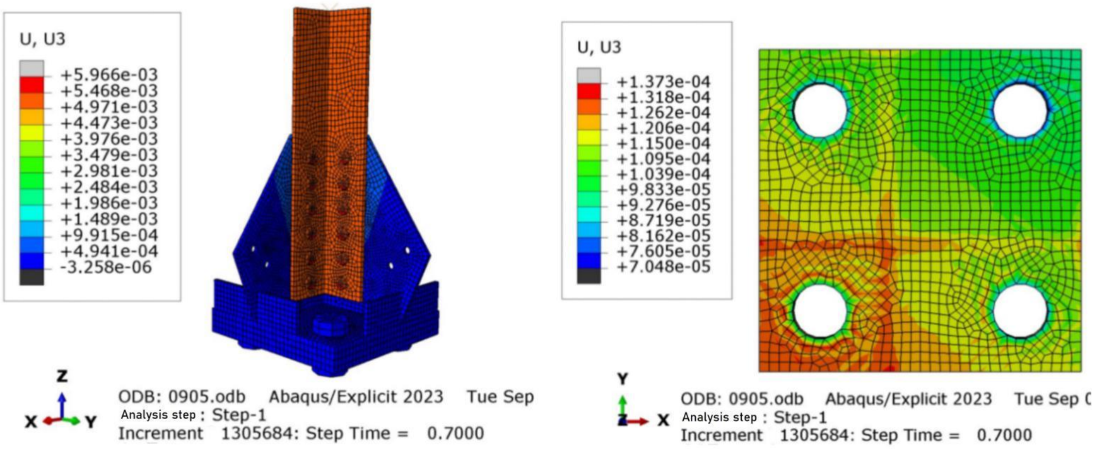
Figure 4. Direction of force illustration

Result Analysis

The failure situation obtained from the finite element software ABAQUS is shown in Figure 5(a), where the connecting bolts between the boot plate and the main angle steel experience shear failure on the contact surface, resulting in a ultimate bearing capacity of 769 kN and a safety margin of about 40%. From Figure 5(b), it can be observed that when the vertical displacement of the main angle steel reaches 6mm, the bolts of the main angle steel experience shear failure. It is suggested to enhance the shear resistance of the main angle steel bolts to improve the node's bearing capacity. The node base plate is divided into four zones according to the boot plate position. From the vertical displacement cloud map of the base plate shown in Figure 5(c), it is evident that the maximum vertical displacement is located at the free edge of the smallest zone of the base plate. Since this area is not damaged, the vertical displacement of the base plate is not considered as a controlling parameter for failure criteria.



(a)Stress Contour



(b) Vertical Displacement Contour

(c) Vertical Displacement Contour of Base Plate

Figure 5. Finite Element Overall Analysis of the Connecting Node

COMPARISON OF CODE CALCULATIONS

To analyze the finite element calculations of the connecting node and compare the results with the code-based calculations, the thickness of the node base plate is used as the main comparison parameter for bearing capacity. The dimensions of the boot plate and stiffener plate are configured according to the construction requirements. Based on the original design specification "Technical Regulations for the Design of Overhead Transmission Line Towers" SDGJ94-1990, section 9.5.2, the thickness of the node base plate is calculated using the zone method as follows:

$$t \geqslant \frac{1}{1.1}\sqrt{\frac{3T\cdot Y_{\max}}{4b_{\min}\cdot f}} \tag{1}$$

Where:

T - Tensile force acting on the base plate (N)

Ymax - Maximum distance from the bottom bolt center to the main angle steel (mm)

bmin - Minimum width of each section of the base plate (mm)

According to the current code "Technical Specifications for Design of Overhead Transmission Line Tower Structures" (DL/T 5486-2020)[17], section 7.9.2, the thickness of the node base plate is calculated using the yield line method as follows:

$$t = \max\left(t_1, t_2\right)$$

$$t_1 = \sqrt{\frac{1.21T}{f_y / r_R} / \left(\frac{L}{b_1 - y_1} + \frac{2b_1}{y_1}\right)} \quad (2)$$

$$t_2 = \sqrt{\frac{0.48T}{f_y / r_R}\left(\frac{y_2}{b_2}\right)} \quad (3)$$

Where:

T - Tensile force acting on the base plate (N)

L - Length of stiffener plate in segment I (mm)

b1 - Width of segment I (mm)

d1 - Distance from the center of the bottom bolt to the boot plate in segment I (mm)

d2 - Distance from the center of the bottom bolt to the boot plate in segment II (mm)

b2 - Width of segment II (mm)

When the connecting node is under compression, the pressure between the base plate and the foundation is not evenly distributed due to the relatively large vertical stiffness of the boot plate and stiffener plate, and the relatively small vertical stiffness of the base plate. Therefore, the bending moment borne by the base plate is relatively small, and the thickness of the base plate is generally not controlled under compression conditions[18]. Hence, the maximum uplift force after considering the working condition combination is used for comparison. The calculated results are as follows:

Table 3. Comparison of base plate thickness calculation results

Base Plate Thickness(mm)	Uplift Force(550kN)	Uplift Force(769kN)
Original Design Code Calculation	33.7	39.9
Current Code Calculation	28.8	34
Finite Element Calculation	20.1	31

From Table 3, it is evident that considering the overall force and plastic performance of the connecting node, the finite element calculation yields a relatively smaller result for the thickness of the base plate compared to the code-based design, effectively utilizing the material performance. Although the original design specification provides a large safety margin, the current code, even with improvements, still maintains a significant safety margin. Therefore, the calculation of the node's bearing capacity based on the code simplification leads to a considerable deviation from the actual situation.

REINFORCEMENT SCHEME DESIGN

Structural Design

Based on the finite element analysis, the failure of the connection nodes between the tower and the foundation is attributed to insufficient shear resistance of the bolts connecting to the main material. To enhance the shear resistance of the connection nodes, ensuring that the safety margin matches that of the upper structure after reinforcement, three reinforcement schemes are designed as follows:

Reinforcement Scheme One: Increase Bolt Shear Strength and Add Side Bolts for Shear Resistance

The construction drawing specifies the use of Grade 6.8 bolts for the node-to-main material connection. However, it has been calculated that bolts of this grade are insufficient to withstand the shear forces generated by the working conditions. Therefore, reinforcement scheme one involves using higher strength bolts with better shear resistance, ensuring that the threads do not enter the shear plane. Additionally, the single-side bolts are to be doubled to create dual-side bolts (as shown in Figure 6). Corresponding holes will be added to the base plate, connecting the additional shear-resistant bolts to the original base plate and the reinforced cross-angle steel. According to the requirements of the construction specification [19], due to limited space at the original base plate position, considering the maximum and minimum allowable distances between bolt holes and edges, only two holes can be added.

Reinforcement Scheme Two: Increase Shear Plane Quantity

The original single shear plane is to be increased to a double shear plane by adding L100×10 angle steel inside the original 110mm-wide main angle steel. The added angle steel should be at least 325mm long and welded to the bottom of the angle steel, requiring hole drilling and welding on one side, thus presenting relatively higher construction difficulty.

Reinforcement Scheme Three: Increase Bolt Hole Diameter and Bolt Size

Replace the original Grade 6.8 M16 bolts with Grade 8.8 M20 bolts to increase the shear resistance area. This requires on-site expansion of the hole diameter from 17.5mm to 21.5mm, making it difficult to control construction quality. Moreover, the process of damaging the galvanized layer during construction needs to be restored.

Taking into account that the current project is aimed at an operational transmission line, ensuring construction quality without power outage and coordinating with the reinforcement method for the upper main material, it is recommended to choose scheme one for the design of the reinforcement device (see Figure 6). This reinforcement device includes the edge base plate, L-shaped boot plate, and stiffener plate; connecting the edge base plate to the additional anchor bolts effectively enhances the tower's uplift capacity. By setting the L-shaped boot plate on both sides opposite to the original boot plate, the bolts connecting with the main angle steel change from single-side shear to double-side shear, enhancing the bolt's shear resistance while effectively coordinating with the reinforcement form of the upper structure's main angle steel, such as cross reinforcement, single reinforcement, or clamping reinforcement. Meanwhile, a stiffener plate is set at the end of the edge base plate to enhance its rigidity and prevent warping deformation.

Finite Element Analysis of Connection Nodes After Reinforcement

According to the structural design scheme for reinforcement described above, a double-line model as shown in Figure 2 is used for calculation, and high-strength Grade 10.9 bolts are used for the connection between the main angle steel and the nodes, with the reinforcement stiffener plate and base plate bound. The stress cloud diagram (Figure 7) when the model undergoes structural failure indicates that even after reinforcement, shear failure still occurs in the connecting bolts of the main angle steel. At this point, the uplift force on the main angle steel is approximately 1045kN, representing an increased bearing capacity of about 35%.

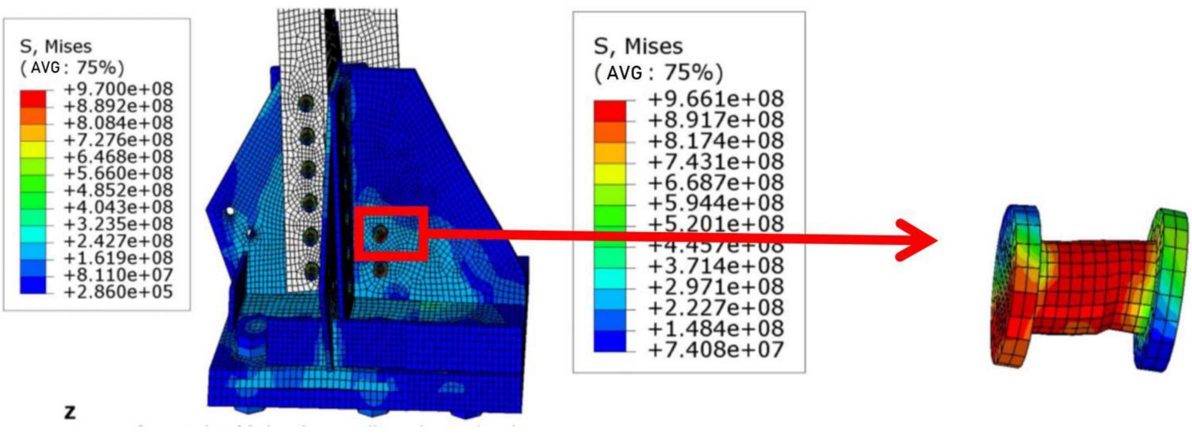


Figure 6. Finite element analysis results of connection nodes after reinforcement

FULL-SCALE TEST

Experimental Design

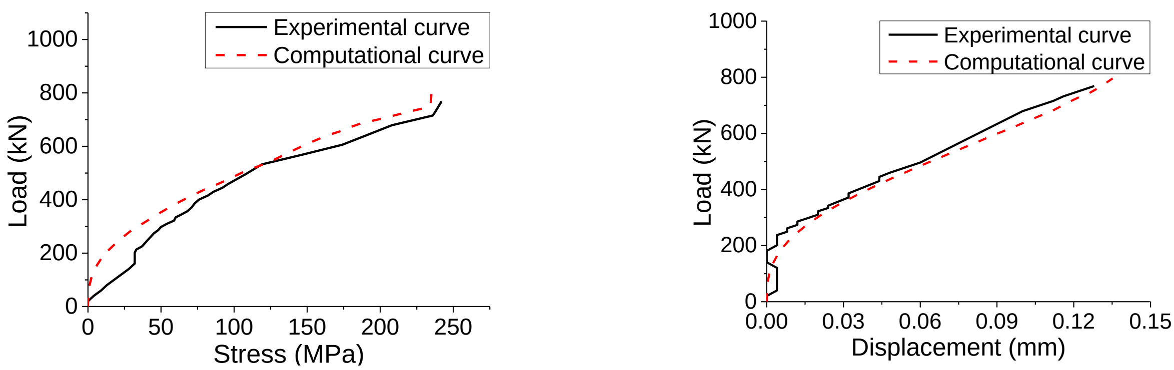
To validate the rationality of finite element calculations and the stress characteristics of connection nodes, test specimens were fabricated according to the construction requirements specified in technical guidelines. Two groups were set up: one with unreinforced connection nodes and the other with reinforced connection nodes for comparison. Strain gauges were installed on the base plate and shoe plate to measure strain, while displacement transducers were placed at locations with higher strain based on finite element simulations. Additionally, displacement transducers were strategically positioned as reference points to measure the deflection of the base plate. The experimental setup is depicted in Figure 7.

Figure 7. Load-bearing capacity test on connection nodes

The experiment involved monotonic static loading, with incremental loading stages[20]. The corresponding load-induced strains and displacements were recorded. The loading was stopped when the maximum vertical displacement of the base plate exceeded 1.5mm, which was determined based on the calculated ultimate load.

Comparison of Experimental and Theoretical Analysis Results

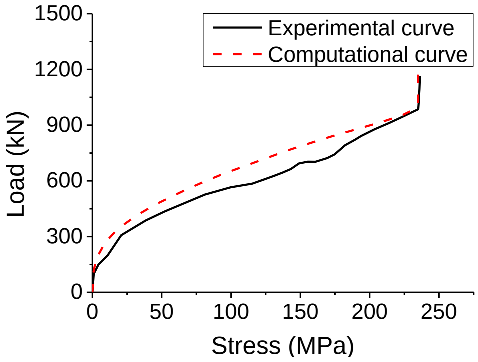
The experimental tests provided data on the stress distribution and deformation characteristics of the connection nodes during loading. On the other hand, finite element analysis simulated the effectiveness of reinforcement measures and yielded stress distribution and deformation data. Figures 8(a) and 8(b) illustrate the comparison between experimental and theoretical data for the unreinforced connection nodes, while Figures 9(a) and 9(b) represent the comparison for the reinforced connection nodes.



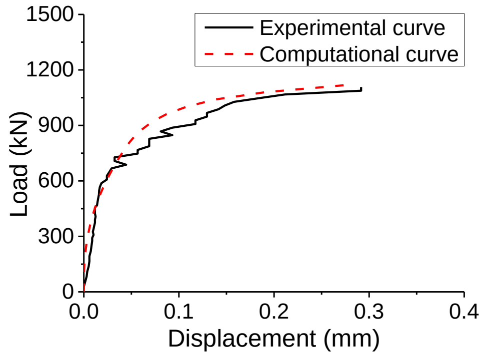
(a) Stress-Load Curve at Maximum Stress Point before Reinforcement

(b) Displacement-Load Curve at Maximum Displacement Point before Reinforcement

Figure 8. Comparison chart of mechanical performance data of connection nodes before reinforcement



(a) Stress-Load Curve at Maximum Stress Point after Reinforcement



(b) Displacement-Load Curve at Maximum Displacement Point after Reinforcement

Figure 9. Comparison chart of mechanical performance data of reinforced connection nodes

Based on Figures 8 and 9, it can be observed that both the unreinforced and reinforced nodes experienced shear failure at the bolt connections of the angle steel, with clean and even fracture surfaces, consistent with the finite element simulation results. The errors in terms of load-bearing capacity, vertical displacement of the main angle steel, and significant deformations for both reinforced and unreinforced cases were within 5%. These findings indicate that the selection of parameters for the finite element model in this study was reasonable, and the analysis results were accurate and reliable, providing an effective evaluation of the accuracy and feasibility of the reinforcement measures.

CONCLUSION

1. The overall safety margin of unreinforced connection nodes was approximately 40%, with the failure occurring due to insufficient shear resistance of the bolt connections between the shoe plate and the main angle steel. The stress ratio of the shoe plate, stiffening plate, and base plate was relatively low, and the maximum deflection of the base plate was less than 0.2mm, which did not exert controlling effects. Thus, strengthening the shear strength of the bolt connections with the main angle steel is necessary for connection node reinforcement.

2. The current design code simplifies the calculation of the base plate thickness using zone method, neglecting the influence of the shoe plate and stiffening plate on the stress distribution in the base plate. In this study, a three-dimensional solid element finite element model of the connection node was employed, which provided more realistic representation of the overall load-bearing capacity of the connection node compared to the current design code. Depending on the applied foundation loads, the base plate thickness could be reduced by 8% to 30%.

3. Existing research on the reinforcement of in-service transmission line towers mainly focuses on theoretical aspects, without considering practical issues such as manufacturing, installation, corrosion protection, and non-power-off construction. In this study, the design of connection node reinforcement was based on three-dimensional solid element finite element modeling, combined with stress analysis and full-scale test assembly. This approach not only validated the adaptability of finite element calculations but also effectively examined critical practical issues, such as possible interference between the reinforcement device and the existing components, adequate installation clearance, and opening compatibility between the upper tower structure and the foundation. The research methodology can provide valuable experience and references for similar steel structure reinforcement projects.

4. As the operating time of domestic transmission lines increases, there will be a need to assess the remaining service life and resilience of these lines. Considering the rapid development of urbanization and the increasing scarcity of land resources for transmission line corridors, reinforcement and strengthening measures are becoming more favorable compared to demolition and reconstruction. Through the comparative analysis of different reinforcement schemes, this study proposed a connection node reinforcement device that is easy to construct, safe, reliable, and economically feasible. This device can effectively cooperate with various structural forms of upper tower structures, such as cross-shaped reinforcement, T-shaped reinforcement, or clamp-type reinforcement, ensuring that the reinforcement device, original connection nodes, and upper structures share the load. The research findings on connection node reinforcement not only contribute to enhancing the value of transmission line assets throughout their life cycle but also lay the foundation for overall reinforcement of transmission lines in the future.

FUND PROJECT

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