Research on the force mechanism of the connection between the foundation ring and the anchor cage ring of the high-altitude onshore wind turbine

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Abstract - The most widely used connection form of the wind turbine foundation and the tower is the foundation ring method. With the popularization and application of high wheel hub and large-capacity wind turbines, the anchor cage ring has gradually become the connection method of large-capacity wind turbines. Therefore, the force mechanism of the connection between the foundation ring and the anchor cage ring has become an important issue in the basic design of the wind turbine. In this paper, numerical simulation method is used to analyse the characteristics of the two connection methods and force characteristics of the foundation ring and anchor bolts. The force transmission mechanism and force characteristics of the two connection methods are summarized and the stress distribution of the foundation ring, the anchor cage ring and the nearby concrete are obtained. Finally, the basic strengthening strategies under the two connection methods are clarified.

1. Introduction
There are several types of connection between the wind turbine foundation and the tower, the most representative ones are the foundation ring and the anchor cage ring. According to incomplete statistics, more than 95% of the wind turbine towers and foundations of domestic wind farms have been built in the form of foundation rings at present. However, with the popularization and application of high wheel hub and large-capacity wind turbines, anchor cage rings are adopted in the connection between the wind turbine towers and the foundation and are widely applied. The connection methods have direct effect on the safety operation of the turbine, so the optimization of the connection between the wind turbine tower and the foundation is particularly important [1-7].

At present, there is little analysis of the force among the foundation ring, anchor cage ring and the adjacent foundation concrete. The performance comparison and application scenarios of the two connection forms lack systematic investigation. Based on the analysis of the wind turbine foundation accident, Yao Dekang et al. [4] compared the two connection methods (foundation ring and the high-strength anchor bolt) with different foundation and superstructure, and concluded that the connection method of the foundation ring with the inner and outer bolts is safer and more reasonable. Ma Renle and Huang Dongping [5] pointed out the sub-health problem of the foundation ring of the upper tower with low fatigue effect and poor crack resistance of the lower concrete. They proposed that the use of pre-
stressed bolts to connect the tower and the foundation is more beneficial to the force of the foundation. By testing the site of the fan foundation accident, Wang Hongwei [6] put forward a reinforcement plan for filling foundation cracks with high-density epoxy grouting. Jia Xingjian et al. [7] tested the tower vibration of the wind turbine with the cracked foundation and the intact foundation under the same conditions. They found that the foundation cracks had a greater impact on the vibration of the tower, especially the vibration at the top. Based on the experimental results of the physical model of the force of the foundation ring, the ANSYS finite element software is used to analyze the stress distribution of the foundation ring, the anchor cage ring and the nearby concrete.

2. Foundation Simulation Model

The load of the wind turbine is transmitted to the concrete through the foundation ring or the anchor cage ring, and then to the steel bar. The load of the wind turbine is determined by the extreme load of a specific wind turbine. In this study, the horizontal load is 832 kN, with the vertical one being 2997.7 kN. The bending moment is 60785 kN·m⁻¹, and the safety factor is 1.0. According to statistics data of the size of the foundation ring of the wind turbine used in China currently, the depth of the foundation ring is about 1.1 m−1.9 m, the width of the bottom flange of the foundation ring is about 240 mm−500 mm, and the thickness of the bottom flange is about 50 mm−120 mm. The values are distributed uniformly within the statistical range.

![Figure 1 The finite element model of the foundation](image)

The finite element analysis was carried out using the ANSYS Workbench platform. The SOLID186 elements were used to simulate the foundation ring, anchor cage ring, and foundation concrete. The focus of this simulation is to analyze the force transmission of the foundation ring and the force of the concrete without considering the nonlinearity of concrete materials and the interaction between foundation and soil. The bottom of the concrete foundation is considered as consolidation. The contact between the bottom flange of the foundation ring and the concrete foundation is simulated by the Mohr-Coulomb friction model with a friction coefficient being 0.6. The sidewall of the foundation ring and the concrete adopt frictionless contact strategy. The concrete elastic modulus Ec of C40 concrete is 3.25×10⁴ MPa with the Poisson ratio being 0.167. The elastic modulus Es of the foundation ring is 2×10⁵ MPa with Poisson ratio being 0.3. The current research results show that the action of the flange at the bottom of the foundation ring results in a large local stress in the foundation concrete. In engineering practice, the pressure-bearing mesh reinforcement is installed under the foundation ring. In finite element analysis, the establishment of the reinforcement model does not have influence on the
simulation results. Therefore, this modeling mainly studies the local compressive stress distribution of the bottom flange, and the influence of steel bars is ignored.

![3D assembly of anchor bolt](image)

Figure 2 3D assembly of anchor bolt

3. Test Results and Discussions

3.1. The Force of the Foundation Ring

The maximum compressive stress of the foundation concrete appears at the outer edge of the bottom flange of the foundation ring on the tension side with the maximum value being 34.01 MPa (stress concentration phenomenon). As shown in Fig 3, the average value of the concrete compressive stress above the bottom flange is 14.52 MPa, which is less than the C40 concrete standard compressive strength value (26.8 MPa). The maximum value of the concrete compressive stress under the ring bottom flange of the foundation on the compression side is 26.8 MPa, and the average value is 15.48 MPa, which is less than the C40 concrete standard compressive strength value 26.8 MPa.

![Profile of the third principal stress of concrete](image)

Figure 3 Profile of the third principal stress of concrete
It can be seen from the Fig 4 that in the case of no reinforcement, the maximum principal stress of the foundation concrete exceeds the standard value of the concrete axial tensile strength in a small range. The larger stress is concentrated on both sides of flange under the foundation ring and the bottom of the compression side. The direction of the principle tensile stress on both sides of flange under the foundation ring is mainly vertical, and steel bars can be configured to bear the tensile stress in the regions with maximum principal stress out of limit.

Figure 4 Contour of maximum principal stress

Figure 5 Regions with maximum principal stress out of limits

The direction of the principle tensile stress under the foundation ring on the compression side is horizontal and radial, and reinforcement should be increased at the bottom plate under the foundation ring during the process of foundation reinforcement.

With the influence of the internal concrete and the stiffness of the foundation ring taken into consideration, the maximum horizontal stress on the top surface of the foundation is 2.7 MPa, which appears at the outer edge of the compression side of the foundation ring and is much smaller than the compressive strength of C40 concrete.
Figure 6 The lateral stress of the foundation ring

Figure 7 Foundation ring stress

It can be seen from the equivalent stress contour of the foundation ring that the maximum equivalent stress of the foundation ring is 237 MPa, which is less than the yield strength of Q345 steel (345 MPa). This indicates that the structure of the foundation ring meets the design requirements.

Furthermore, under extreme load, the foundation ring itself will not yield and fail during the force transmission process, and the entire foundation will not be damaged. But the concrete at the bottom of the flange may be crushed due to local compressive stress. It is concluded that it is necessary to strengthen the reinforcement during the foundation design process.

3.2. The Force of the anchor bolt form

Under extreme conditions and loads, the axial stress contour of the pre-stressed anchor bolt is shown in Figure 8. The maximum axial tensile stress is distributed in the positive direction of the Z axis, which is 347.1 MPa and is less than its yield strength of 660 MPa.
Under extreme load, the vertical stress contour of the XZ section of the pre-stressed anchor bolt is shown in the following figure. The maximum pressure of the grouting material appears at the bottom surface of the flange on the opposite side of the main wind direction. The local pressure of the grouting material is 37.6 MPa, and the compressive strength of the grouting material must not be less than 100 MPa. The maximum pressure of the foundation concrete at the bottom of the grouting material is 22.8 MPa, which exceeds the limit value of C40 concrete compressive strength. Therefore, it is necessary to consider the configuration of square mesh reinforcement. It can be seen from the compression profile of the foundation concrete that the concrete is under compression near the anchor bolts, which can avoid the occurrence of cracks. The maximum Von-Mises stress of the flange is 35.7 MPa, being much smaller than the flange yield strength.

It can be observed that under extreme load, the anchor cage ring itself will not yield and fail during the force transmission process. The entire foundation will not be damaged, and the concrete near the anchor bolt is in a compressed state to avoid cracks. The high-strength grouting material at the bottom of the upper anchor plate and the foundation concrete have large local compressive stresses. During the foundation design process, it is necessary to ensure the sufficient strength of the grouting material and to configure mesh reinforcement in the foundation concrete under the grouting material.
Figure 10 The compression profile of the foundation concrete

Figure 11 The vertical stress contour of the XZ section of the pre-stressed anchor bolt

Figure 12 The Von-Mises stress of the flange
4. Conclusion
In this paper, the stress distribution of the foundation ring, the anchor cage ring, and the foundation concrete are studied separately based on the force characteristics of the wind turbine tower and the foundation. It is found that under the extreme loads, the foundation ring itself will not yield and fail during the force transmission process. However, the local compressive stress of the concrete at the bottom of the flange is too large, which exceeds the strength limit of the concrete. Hence the reinforcement is needed in the foundation design process. The situation of the anchor cage ring is like that of the foundation ring. The anchor cage ring itself will not yield and fail during the force transmission process, and the entire foundation will not be damaged. However, the local compressive stress of the concrete near the anchor bolt is large, and it is necessary to configure mesh reinforcement for the grouting material in the foundation design.

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References
[1] Deng Y, Li W, Wang Q, et al. Structure types of wind turbine foundation and its calculation methods[J]. Science Technology and Engineering,2020,20(21):8429-8439.
[2] Liu M, Yang M. Interaction between foundation ring and concrete of wind turbine[J]. Acta Nergiae Solaris Sinica,2017,38(7):1973-1978.
[3] Li D, Huang Z, Gao H, et al. The bearing behaviors of the wind turbine foundation with various burial depths and flange widths[J]. Renewable Energy Resources,2016,34(5):719-724.
[4] Yao D, Wang M, Xue Z. Design Analysis of Wind Turbine Tower Foundation[J]. Steel Construction,2011,26(06):20-23.
[5] Ma R, Huang D. Belled Pile Foundation Design of Wind Power Generator in Regions of Collapsible Loess[J]. Special Structures,2012,29(04):50-52+55+4.
[6] Wang H. Cause Analysis and Grouting Reinforcement on Loose Foundation Ring of Wind Turbine[J]. Journal of Safety Science and Technology,2016,12(03):104-107.
[7] Jia X, Yang X, He X, Yu T. Vibration Test and Analysis of Wind Turbine Towers with Cracks in Concrete Foundations[J]. Noise and Vibration Control,2017,37(06):163-167+205.