Design of Bolts Structure of Overhead Contract Line Based on Finite Element Method

Xu yong\textsuperscript{1,a}, Lu xiaojuan\textsuperscript{1,b}

\textsuperscript{1}School of Automation and Electrical Engineering, Lanzhou Jiaotong University, Lanzhou, Gansu, China

\textsuperscript{a}email: 1942666895@qq.com

\textsuperscript{b}Corresponding Author: email: Luxj@mail.lzjtu.cn

Abstract: The existing factory-type bolts of Overhead Contract Line are easy to fall off after installation. In order to solve this problem, firstly, a new type of factory-type bolts that can fasten concrete pillars is proposed for the purpose of clamping and fastening reliability and safety. This new type of factory-type bolts adds a T-type bolts and locknut on the basis of the original factory-type bolts. Secondly, the theoretical calculation formula of the maximum stress when the stress is concentrated in the circular hole on the bolt rod is deduced by using the theory of elasticity. Finally, the finite element method is used to analyze the stress of the new type of factory-type bolts. Research indicates: The simulation verifies the correctness of the theoretical calculation formula, The new factory-type bolts have great practical application value.

1. Introduction

The Overhead Contract Line system is an important part of the railway power supply system, most of which use electrical and mechanical connections\textsuperscript{[1]}. Whether each component is connected firmly or not directly affects the stability of the system. Whether or not the factory-type bolts of the parts are fastened to the concrete pillars has a great influence on preventing the inclination of the pillars. Fastening is the basic guarantee for the safety, stability and reliability of the Overhead Contract Line, and it is of great significance to ensure the safe operation of the train.

Scholars at home and abroad generally use the simplified structure formula derivation method to calculate when analyzing the structure of the existing Overhead Contract Line components\textsuperscript{[2]}. Zhao Jinfeng\textsuperscript{[3]} proposed the use of finite element to optimize the design of Overhead Contract Line components. The stress distribution and deformation of the components can be clearly seen under the action of external force, which provides a powerful verification method for the design of new components. Huang Yi and others\textsuperscript{[4]} researched and designed prestressed anchorages for railway components. However, few researchers have analyzed the existing plant-type bolt structure and proposed a new type of plant-type bolt structure design.

In engineering practice, it is found that there are certain defects in the existing plant-type bolt design structure. The article by Xu Yong\textsuperscript{[5]} theoretically solves the problem of the plant-type bolt head falling down by using the principle of torque balance, but there are two shortcomings in the article. 1. The anti-skid parts adopt pins made of iron wire, and the pin design is relatively rough. 2. The factory-type bolts after drilling have not been checked for strength and rigidity, and cannot be widely used in engineering practice. Based on the above analysis, under the guidance of the design principles,
this paper proposes a new type of plant-type bolt structure after comprehensively considering various factors, and uses the finite element method to perform stress analysis on it. Finally, a new type of bolt structure of the catenary plant with innovation, practicability, economy and safety is designed.

2. Plant type bolt structure design

For products other than insulators (including various bases and pillar products), due to the static load, the typical anti-loosening measure is a nut + flat washer structure\cite{6}. Based on on-site construction practice, it is proved that this kind of anti-loose measures has certain shortcomings in using factory-type bolts to fix horizontal slabs and pillars. Factory bolt fall off As shown in Figure 1.

In order to solve the problem that factory-type bolts are easy to fall off and the design of anti-skid pins of factory-type bolts in the introduction is rough and so on. The anti-skid parts of the new structure adopt fasteners. According to the working principle of anti-loosening of contact net fasteners, it can be divided into friction anti-loosening, mechanical anti-loosening, and anti-loosening of the thread pair relationship, such as: spring washers, double nuts, split pins, brake washers, etc\cite{7}. The design structure of threaded connection is further proposed. The selection of bolts needs to consider two factors: 1. The diameter of the bolt T-shaped surface is close to or reaches the diameter of the factory-type bolt, which is beneficial to contact with the inner wall of the pillar to generate a supporting force \( F \). 2. The bolt diameter is as small as possible to reduce the damage degree of the mechanical properties of the factory-type bolts. There are three types of standard T-bolts on the market, M6, M8 and M10, which are intended to meet the design requirements, as shown in Table 1:

| Material/Model | M6 | M8 | M10 |
|----------------|----|----|-----|
| T-shaped surface diameter | 16mm | 20mm | 25mm |
| Bolt diameter | 6mm | 8mm | 10mm |

According to the above table and the bolt selection requirements, the standard matching combination of M6 T-bolt and nut is the best choice. The plan view of the new type of factory bolt is shown in Figure 2.

3. Theoretical calculation of new type factory bolts

Suppose the long cylinder has a small circular hole with radius \( a \) far away from the boundary, and the left and right sides are subjected to uniform Bula force \( q \), as shown in Figure 1. The coordinate origin is taken at the center of the circular hole and the coordinate axis is parallel to the boundary. Establish a large circle with a certain length \( b \) far greater than \( a \) as the radius and the origin of the coordinates as the center of the circle, as shown in Figure 3. At the large circle, the stress state at point A is the same as that without holes\cite{8}, that is
According to the elastic theory, the transformation formula from rectangular coordinates to polar coordinates is

\[
\begin{align*}
\sigma_r &= \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\theta + \tau_{xy} \sin 2\theta \\
\sigma_\theta &= \frac{\sigma_x + \sigma_y}{2} - \frac{\sigma_x - \sigma_y}{2} \cos 2\theta - \tau_{xy} \sin 2\theta \\
\tau_{r\theta} &= \frac{\sigma_y - \sigma_x}{2} \sin 2\theta + \tau_{xy} \cos 2\theta
\end{align*}
\]

Substituting (1) into (2) to get the polar coordinate stress component

\[
(\sigma_r)_{r=b} = q, (\sigma_\theta)_{r=b} = 0, (\tau_{r\theta})_{r=b} = 0
\]

(3) The formula can be divided into two parts, the first part is

\[
(\sigma_r)_{r=b} = \frac{q}{2}, (\tau_{r\theta})_{r=b} = 0
\]

(4) The other part is

\[
(\sigma_r)_{r=b} = \frac{q}{2} \cos 2\theta, (\tau_{r\theta})_{r=b} = \frac{q}{2} \sin 2\theta
\]

So the original problem becomes a new one, that is, a cylinder with an inner radius of a and an outer radius of b is subjected to a surface force like (3) on the outer boundary. In order to obtain the stress caused by the surface force of (4), we can solve it by Lamy and make \( q_r = -q/2 \)

\[
\sigma_r = \frac{q}{2} \left(1 - \frac{a^2}{r^2}\right), \sigma_\theta = \frac{q}{2} \left(1 + \frac{a^2}{r^2}\right), \tau_{r\theta} = 0
\]

(6) And a is much smaller than b, so a/b is approximately 0, and the solution is

\[
\sigma_r = \frac{q}{2} \left(1 - \frac{a^2}{r^2}\right), \sigma_\theta = \frac{q}{2} \left(1 + \frac{a^2}{r^2}\right), \tau_{r\theta} = 0
\]

(7) In order to obtain the stress caused by the face force (5), a semi-inverse solution method is adopted. To get the stress function.

\[
\varphi = \left(Ar^4 + Br^2 + C + \frac{D}{r^2}\right) \cos 2\theta
\]

(8) Then by the stress component of the stress equation in the polar coordinate system
Apply boundary condition (5) to equation (9), and apply boundary condition
\( (\sigma_r)_{r=a} = 0, (\tau_{r\theta})_{r=a} = 0 \)  \( \text{(10)} \)

Get the equation

\[
\begin{align*}
2B + \frac{4C}{b^2} + \frac{6D}{b^2} &= -\frac{q}{2} \\
6Ab^2 + 2B - \frac{2C}{b^2} - \frac{6D}{b^2} &= -\frac{q}{2} \\
2B + \frac{4C}{a^2} + \frac{6D}{a^2} &= 0 \\
6Aa^2 + 2B - \frac{2C}{a^2} - \frac{6D}{a^2} &= 0
\end{align*}
\]

Solve for A, B, C, D, and then command \( a/b=0 \), we get
\( A = 0, B = -\frac{q}{4}, C = qa^2, D = -\frac{qa^4}{4} \)  \( \text{(12)} \)

Then substitute each known value into equation (9) and superimpose it with equation (7) to get
\( \sigma_\theta = q\left(1 - 2\cos2\theta\right) \)  \( \text{(13)} \)

Along the edge of the hole, when \( r=a \), the hoop normal stress is
\( \sigma_\theta = q(1-2\cos2\theta) \)  \( \text{(14)} \)

Its several important values are shown in Table 2:

| \( \theta \) | 0° | 30° | 45° | 60° | 90° |
|---|---|---|---|---|---|
| \( \sigma_\theta \) | \(-q\) | 0 | \(q\) | 2\(q\) | 3\(q\) |

In the same way, when \( a/b=0.3 \), Its several important values are shown in Table 3:

| \( \theta \) | 0° | 30° | 45° | 60° | 90° |
|---|---|---|---|---|---|
| \( \sigma_\theta \) | -0.88q | -0.11q | 0.69q | 1.51q | 2.35q |

It is easy to know that when \( \theta=90^\circ \), that is, along the y axis, the maximum hoop normal stress is
\( \sigma_\theta = 2.35q \)  \( \text{(15)} \)

4. Finite element numerical simulation analysis

4.1 Finite element model

In this paper, a newly designed three-dimensional solid model of factory-type bolts is established through AuTo CAD2010. According to this design, the non-slip parts of the structure adopt the standard matching combination of T-bolts and nuts. It is easy to know that the supporting force of
T-bolts is very small and only a few Newtons. The standard T-bolts on the market can fully meet the requirements of mechanical properties. It is of little significance to the analysis of the mechanical properties of T-bolts, so the connection parts are simplified when modeling. Use the classic version of ANSYS 17.0 to perform stress analysis on the established model. The unit type is Brick 10 node 187. Grid division adopts smart grid division, the division precision is 4. The material parameters of the main components[9] are shown in Table 4:

| Part Name  | material | Elastic Modulus | Poisson's ratio | density |
|------------|----------|-----------------|-----------------|---------|
| Factory bolt | Q235     | $2.06 \times 10^5$ | 0.3             | 7850    |

The restraint is applied to the entire circular surface of the factory-type bolt tail, and the pressure is applied to the inside of the bend of the factory-type bolt. According to the technical requirements of document TB/T3395.1[10], the design buckle pressure of small resistance fasteners is $\geq 3$KN, so input the required load value 4KN. Stress distribution cloud diagram As shown in Figure 4.

4.2. Numerical simulation and result analysis

Through the finite element analysis, the stress distribution cloud diagram of the factory-type bolt is shown in Figure 4. The axial stress at the edge of the small hole multiplied by the area of the force-bearing part of the factory bolt is equal to the simulated value of the stress at the edge of the small hole.

Through the finite element calculation, the following conclusions can be obtained. The maximum stress of the factory-type bolt occurs at the edge of the small hole under the action of force. This also verifies the stress concentration effect at the edge of the hole in elastic mechanics. The maximum equivalent stress is 135MP, the equivalent stress Less than the allowable stress of Q235 steel 156.7MP. From the perspective of theoretical mechanics, the design of the component is reliable within the safety margin. Then compare the theoretical value with the simulated value, see Table 5:

| name              | Theoretical value | Analog value | Relative error |
|-------------------|-------------------|--------------|----------------|
| Hole edge stress  | 9.4KN             | 9.7KN        | 3.0%           |

It can be seen from Table 5 that the theoretical value is slightly lower than the simulated value. This is due to the simplification of the theoretical calculation formula in the derivation process, but
the error between the two is within 5%, which can meet the engineering design requirements. Therefore, the theoretical calculation formula of factory-type bolts is reasonable and can be used to determine the size of factory-type bolts. The actual processing object is shown in Figure 5.

![Fig. 5 Processing physical map](image)

5. Conclusion
This paper designs a new type of factory-type bolts structure. Through theoretical calculations and finite element simulation analysis, the corresponding physical objects were finally made according to the design structure, and the following conclusions were obtained:

1) The newly designed factory-type bolts structure makes up for the insufficiency of the factory-type bolt that is easy to fall off after installation in the previous construction of the lower part of the catenary.

2) A newly designed finite element model of factory-type bolts was established, and the simulated values and theoretical values were compared, and the correctness of the theoretical design formula was verified, which provided a theoretical basis for the size design of factory-type bolts.

References
[1] Liu, Z.G., Song, Y., Han, Y. (2018) Advances of Research on High-speed Railway Catenary. J. Journal of Modern Transportation., 26:1-23.
[2] Bautista, A., Montesinos, J., Pintado, P. (2016) Dynamic Interaction between Pantograph and Rigid Overhead Lines Using a Coupled FEM Multi-body Procedure. J. Mechanism and Machine Theory., 97:100-111.
[3] Zhao, J.F. (2004) Using Finite Element Analysis Method to Optimize the Structural Design of Catenary Parts. J. Electrified railway., 14:9-12.
[4] Huan, Y., Ma, L., Pan, Z.M. (2019) Research and design of slow-bonding prestressed anchorage. J. Railway Construction, 59:54-56.
[5] Xu, Y. (2019) Research on improvement of factory-shaped bolts based on the lower material of the catenary. J. Railway construction technology, 35:72-75.
[6] Go, L. (2013) Collection of Technical Papers on Safety and Reliability of Catenary Components for High-speed Railways. In: China Railway Society. Beijing. pp: 55-57.
[7] Pan, L., Chen, L.M., Yang, C.Z. (2020) Electrified railway contact net fastener anti-loose measures and its fastener research. J. Electrified Railway, 31:37-41.
[8] Qian, W.Z., Ye, K.R. (2006) Stress concentration at the edge of the hole. In: Xu, Z.L. (Eds.), Elasticity. Higher Education Press, Beijing: 98-101.
[9] Li, H.Z., Li, P.B., Huang, S.X. (2020) Finite element analysis and experimental study on the anti-skid performance of new all-steel fasteners. J. Mechanical Design and Research, 36:77-80.
[10] TB/T3395.1-2015 Fasteners for high-speed railways Part 1: General technical conditions [S].