Study on Stress Concentration Phenomenon in Threaded Fasteners

Abstract: This article calculates the stress concentration factor of threaded connections under service conditions through virtual simulation. By applying nonlinear finite element technology, a nonlinear contact finite element model of the specimen is established. The main research of this article explores the fatigue performance of the threaded connection head of lifting cable anchorages, and at the same time provides a theoretical basis for the maintenance and maintenance of threaded connections.

Keywords: Thread; Stress concentration; Stress concentration factor; Virtual simulation simulation

1. Introduction

Research on stress concentration phenomena has been conducted by many scholars from theoretical modeling and finite element simulation perspectives. Among these, the mathematical model proposed by Sopwith D G[1] to describe the load distribution in threaded connections treats the load between threads as a concentrated force acting at the center of the threaded cross-section of the connection. This model and its theory have been widely recognized (Wentzel & Huang, 2015; Guo et al., 2021). Years later, Zhao H[2] adopted the Virtual Contact Loading (VCL) method, based on a simplified axisymmetric model, to simulate the elastoplastic contact phenomenon between threads and analyzed in detail the stress and load distribution along the thread. At the beginning of the 20th century, Lehnhoff T F et al.[3] believed that the geometric shape of the threaded connection has a significant impact on the stress concentration phenomenon of the connection. Through finite element simulation, they proved that reducing the diameter of the bolt can significantly reduce the stress concentration factor of the connection, and the location of the maximum stress is independent of the thread geometry. The following year, Srinivasan G et al[4]. studied the effect of eccentric loading on the maximum stress and the stress intensity factor of the fillet of the threaded connection, finding that these values directly depend on the loading eccentricity and the distance between the radius of inertia moment of the connection and the center axis of the threaded connection.

For further research on stress intensity factors, Guo W et al. [5]studied the influence of different stress concentration factors and notch geometries on the crack stress intensity factor of specimens and provided a general SIF formula for calculating the stress concentration factor for different notch geometries. Through fatigue testing of threaded connections, Guo[6] found that with an increase in the number of fatigue cycles, the threaded connections would experience instantaneous fracture, indicating that the generation of stress concentration at the threaded connection is the root cause of fatigue failure.

2. Virtual Simulation Modeling

During the construction process of a threaded connector model, it is essential to consider various types of threaded connectors and their thread forms, selecting them based on the actual requirements of specific application scenarios. The design phase should fully take into account key factors such as the load-bearing capacity of the threaded connector, the tightness of the connection, self-locking performance, transmission efficiency, and the working environment. By scientifically selecting and applying threaded connectors, the reliability and safety of the connection can be ensured, thereby enhancing the performance and service life of the overall structure. In thread design, the arc transition design at the bottom of standard threads helps to disperse stress, thereby reducing the effect of stress concentration. Such thread structures are frequently used in the engineering field due to their excellent versatility and wide range of applications, becoming the most common type of thread in daily engineering practice.

Apart from thread form, factors affecting the fatigue performance of threaded connectors may include the thread helix angle, also known as the lead angle. The lead angle refers to the angle between the tangent of the helix line on the mean diameter cylinder or cone and the plane perpendicular to the thread axis. It is an important parameter describing the geometric characteristics of the thread and reflects the degree of inclination of the helix line. In threaded connectors, the size of the thread helix angle does indeed affect its fatigue performance. Specifically, too large a helix angle can lead to larger loads on the thread teeth, which can cause fatigue fracture; while too small a helix angle can result in the loss of self-locking of the thread, making it prone to loosening and detachment.

The research model in this study adopts a common thread form and establishes models with and without thread helix angles for comparison, exploring the impact of the thread helix angle on virtual simulation results in the simulation. The following is the specific method of model construction for this study.

(1) Geometric model:

Based on the actual drawings of a certain suspension bridge anchor, a scaled geometric model was established. The specific model is shown in Figure 1 below.

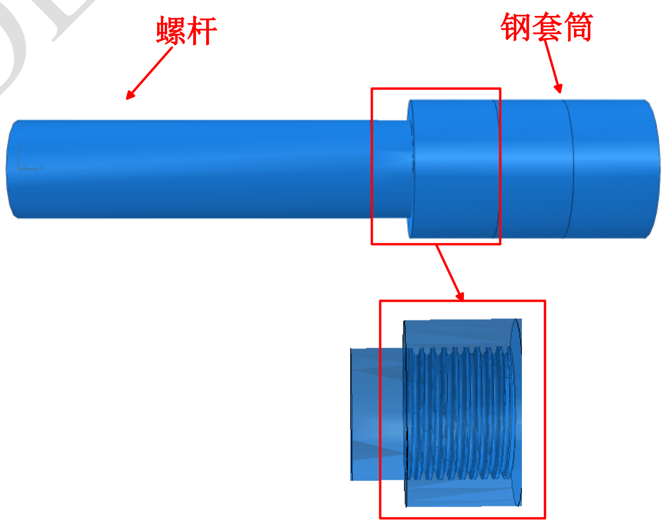

Fig.1 M24 threaded connector model and partial thread diagram

(2) Material properties

In the Abaqus software, define the 40Cr material as elastic and assign the elastic modulus and Poisson's ratio to the geometric model.

(3) Define boundary conditions and loads

During the fatigue testing process of the M24 screw and steel sleeve, the end fixture is set around the end of the steel sleeve to ensure that there is no displacement in the horizontal direction. However, before conducting the fatigue test, it is necessary to adjust the clamping force of the fixture to ensure that there is also no displacement in the vertical direction. Therefore, constraints must be applied to the cylindrical part of the steel sleeve end to limit its degrees of freedom in the X, Y, and Z directions. In the initial analysis phase, the end of the steel sleeve is set to a completely fixed state (U1=U2=U3=UR1=UR2=UR3=0). In analysis phase 1, the load applied to the screw is calculated as a uniform surface load of 221MPa, which is aligned with the Z-axis to ensure that the peak stress value of the bolt thread remains within the elastic range.

(4) Contact Property Settings

During the fatigue test process, the screw and steel sleeve are connected through thread engagement, and there will be no significant displacement during the loading process. For the contact of both ends of the thread, select face-to-face contact, and use the small slip formula for calculation. To prevent mesh distortion at the top of the thread, a certain tolerance is specified for the adjustment area. Set the tangential behavior of the contact properties to the "penalty" function friction formula and the normal behavior to the "hard" contact form, which means that the size of the contact pressure transmitted by the contact surface is not limited. If for the purpose of increasing the convergence of the contact to make the calculation results more accurate, standard contact control can be increased, giving the model an automatic stable factor which will help with the convergence of the model. Since the thread connection is subjected to force on one side, contact parts can be separately established as set collections. The calculation principle of full contact and semi-contact forms is consistent, but it is beneficial for mesh distortion and model convergence issues. The two contact forms are shown in Figure 2.

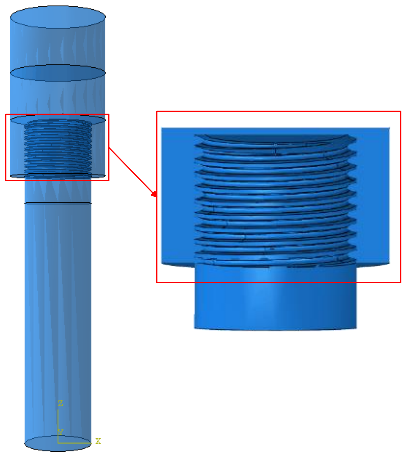

Fig.2 Thread contact form

(5) Element Selection

The M24 threaded connector model is mostly meshed using C3D10 elements, which are 6-node tetrahedral linear reduced integration elements. These elements improve computational efficiency by reducing the number of integration points. Using this type of mesh has several advantages, such as being less prone to shear locking under bending loads and providing relatively accurate results for displacement solutions, etc.

(6) Mesh Division

The M24 threaded connector model focuses on the stress condition at the thread connection between the screw and the steel sleeve. Due to the complex stress distribution at the screw threads and the area of most severe stress concentration, it is necessary to refine the mesh at the thread area, thereby dividing a finer mesh. A method of partitioning the model within the component is adopted, cutting at each position where there is a sudden change in cross-section. Therefore, each thread is an independent area for remeshing. A 5mm mesh size is used for the steel sleeve and screw non-focus areas, some transition areas use a 3mm mesh size, and the thread connection area adopts a 1.4mm mesh size for encryption processing. The specific mesh division is shown in Figure 3

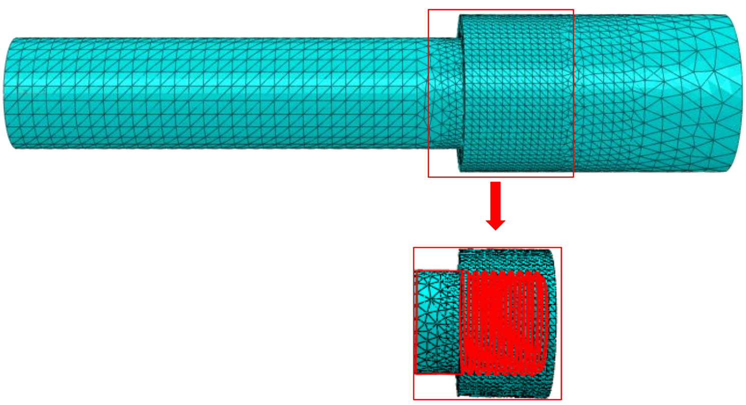

Fig.3 Mesh division of M24 threaded connector component model

3. Post-processing analysis of simulation models

According to the finite element stress nephogram of the M24 threaded connector, the position of the greatest finite element stress concentration is at the first thread root where the screw engages with the steel sleeve, which is consistent with the theoretical fatigue test fracture location. The stress concentration area of the steel sleeve is located at the outermost thread of the sleeve, which shows some differences from the fatigue test results. The calculation results of the finite element model are shown in Figure 4.

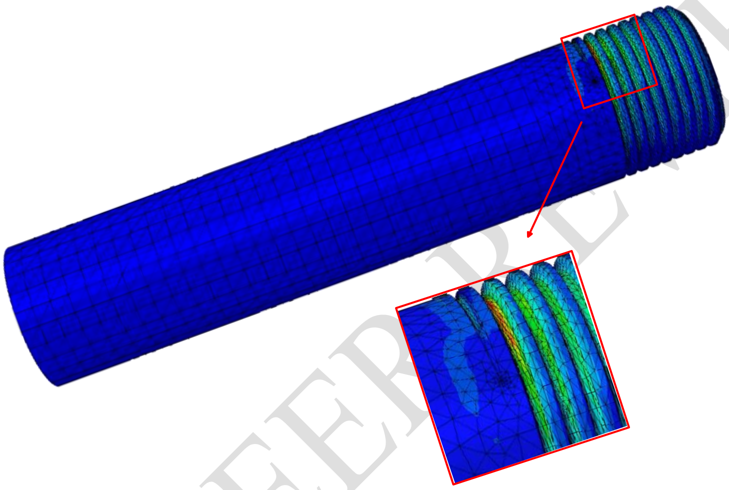

Fig.4 M24 threaded connector finite element stress concentration area

Based on the virtual law simulation results, the stress distribution of each component of the M24 threaded connector is derived. According to the illustration, the stress distribution on the external thread part of the bolt is uneven and shows a rapid fluctuation trend, with the peak occurring at the first thread engagement between the bolt and the steel sleeve.

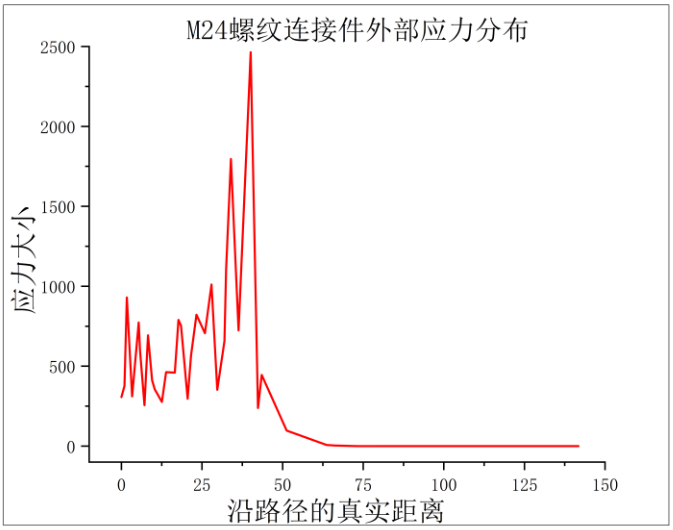

Fig.5 External stress distribution of M24 threaded connector screw

The calculation of the stress concentration factor requires the maximum stress value and the nominal stress. The nominal stress is calculated based on the results of virtual simulation. Nominal stress refers to the stress calculated on the effective cross-section of the sample without considering geometric discontinuities (such as holes, grooves, belts, corrugations, etc.). It is a holistic equivalent stress and not the actual local force acting on the structure. For example, in the case of honeycomb or foam structures under pressure, their nominal stress equals the force divided by the area (equivalent to a continuum), but the actual local stress in the structure should equal the force divided by the material area on the cross-section. Therefore, according to the definition of nominal stress, this study extracts the nodal stresses at the section where the stress maximum point is located and calculates the average stress on that section, which is equivalent to the nominal stress.

Extract the stresses of all nodes at the section where the maximum stress occurs for the M24 threaded connection bolt based on the virtual simulation results and calculate the average value, which is the nominal stress of the bolt.

$$\sigma_0 = \sum_{i=1}^{n} \sigma_i / n = 802.47MPa$$

Based on the virtual simulation results of the M24 threaded connection, the maximum Mises stress of the bolt and the calculated nominal stress are obtained:

$$K_t = \frac{\sigma_{\max}}{\sigma_0} = 3.28$$

4. Discussion and analysis

1、 According to the virtual simulation test of threaded fasteners, the stress concentration phenomenon occurs at the first thread of the screw and the steel sleeve, which is consistent with reality.

2、Based on the analysis and calculation of the stress concentration phenomenon, the stress concentration factor of the threaded fastener is determined to be 3.28, providing a basis for future engineering and experiments

References

[1] Sopwith D G. The distribution of load in screw threads[J]. Proceedings of the Institution of Mechanical Engineers, 1948, 159(1): 373-383.

[2]Zhao H. Stress concentration factors within bolt-nut connectors under elasto-plastic deformation[J]. International Journal of Fatigue, 1998, 20(9): 651-659.

[3]Lehnhoff T F, Bunyard B A. Bolt thread and head fillet stress concentration factors[J]. J. Pressure Vessel Technol., 2000, 122(2): 180-185.

[4]Srinivasan G, Lehnhoff T F. Bolt head fillet stress concentration factors in cylindrical pressure vessels[J]. J. Pressure Vessel Technol., 2001, 123(3): 381-386.

[5]Guo W, Shen H, Li H. Stress intensity factors for elliptical surface cracks in round bars with different stress concentration coefficient[J]. International journal of fatigue, 2003, 25(8): 733-741.

[6]Guo H， Mao K， Liu Y， etal. Experimental study on fatigue performance of Q460 and Q690 steel bolted connections[J]. Thin-Walled Structures， 2019， 138: 243-251.He L H, Li Z R. Impact of surface stress on stress concentration[J]. International Journal of Solids and Structures, 2006, 43(20): 6208-6219.

[7]CE I. Stresses in a plate due to the presence of cracks and sharp corners[J]. Trans Inst Naval Archit, 1913, 55: 219-241.

[8]Pilkey W D, Pilkey D F, Bi Z. Peterson's stress concentration factors[M]. John Wiley & Sons, 2020.

[9]Kirsch, 1898, Die Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. Zeitschrift des Vereines deutscher Ingenieure, 42, 797－807.Hetenyi M. A photoelastic study of bolt and nut fastenings[J]. 1943.

[10]Li Z, Zhao Z, Zhang J, et al. A novel experimental method for bolt stress distribution during the assembly process[C]//Structures. Elsevier, 2024, 69: 107413.

[11]Xu H, Shi T, Zhang Z, et al. Loading and contact stress analysis on the thread teeth in tubing and casing premium threaded connection[J]. Mathematical Problems in Engineering, 2014, 2014(1): 287076.

[12]Pan Q, Pan R, Shao C, et al. Research review of principles and methods for ultrasonic measurement of axial stress in bolts[J]. Chinese Journal of Mechanical Engineering, 2020, 33: 1-16.

[13]Sopwith D G. The distribution of load in screw threads[J]. Proceedings of the Institution of Mechanical Engineers, 1948, 159(1): 373-383.

[14] Wentzel, H., & Huang, X. (2015). Experimental characterization of the bending fatigue strength of threaded fasteners. *international Journal of Fatigue*, *72*, 102-108.

[15] Guo, K., Zhang, T., & Yuan, H. (2021). Experimental and computational investigations of nonlinear frictional behavior in threaded fasteners. *Tribology International*, *154*, 106737.