Self-loosening Analysis of Bolted Joints

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Keywords: Bolted joints, Self-loosening, Clamping force.

Abstract. Bolted joint is one of the most widely used connections because of relatively simple structure, reliability, easy disassembly and maintenance. However, self-loosening of bolted joints under cyclic external loading is still an unsolved issue and need to make a further research. As is known to all, the self-loosening process can be divided into two distinguishable stages under cyclic transverse loading. The first stage is featured by a short and sharp clamping force reduction with no relative rotation between the nut and the bolt. The loss of the clamping force is due to the accumulation of local cyclic plastic deformation at the root of the engaged thread, which is account for no more than 10-15%. Therefore, the second stage is the primary cause of self-loosening. In this study, a further research on the second stage self-loosening of bolted joints is presented by the ways of combining theoretical analysis with the three-dimensional finite element simulation. The nature of the second stage self-loosening of bolted joints lies in: 1) the variation of the contact pressure between the engaging thread surfaces, 2) lateral micro-slip between the engaging thread surfaces. Both of them result in an apparent slip between the engaging thread surfaces of bolt and nut which finally leads to the self-loosening of bolted joints. In addition, the effects of preload, amplitude of cyclic transverse loading and the friction coefficient of engaging surfaces on self-loosening are studied by the finite element simulation. Moreover, a reasonable explanation of the trend about the self-loosening of bolted joints is given. The corresponding results are very important for the bolted design. It can be concluded that reasonable preload may improve the ability of bolted joints resisting to self-loosening.

Introduction

Bolted joint is one of the most widely used connections because of relatively simple structure, reliability, easy disassembly and maintenance. However, bolted joints will cause fatigue or self-loosening under cyclic external loading, finally leading to the failure of screw fracture or insufficient clamping force. Fatigue failure of mechanical structure under cyclic external loading is always a very hot issue. Nevertheless, self-loosening is also an important reason for the failure of bolted joints because it results the gradual loss of the clamping force under cyclic external loading, especially for transverse loading. Hence, in recent years, the researches on self-loosening of bolted joints become active. Early investigations concentrate on the behaviors of bolted joints under axial dynamic loading. Junker [1] firstly noticed the
importance of the lateral dynamic load to the occurrence of self-loosening. A new test machine was built to demonstrate this hypothesis. Yamamoto and Kasei [2] developed quantitative models based on a two-stage theory for the nut sliding along the thread of the bolt. However, no quantitative results were provided for the verification of the models. Based on Junker’s basic assumptions, Sakai [3, 4] carried out a theoretical analysis, and attempted to derive the necessary conditions for a bolt to loosen by self-rotation. Their results indicated that unless the friction coefficient was less than 0.03, the self-rotation of the bolt would not be happened. And one of the causes of the clamping force relaxation was the fretting wear between contact surfaces.

Kasei et al. [5] firstly studied the initial stage of self-loosening. The initial loss of the clamping force was attributed to the repeated twist of the nut relative to the bolt shank because of the slippage between the bolt and nut threads. Yanyao Jiang and Ming Zhang [6,7] proposed that bolted joints will occur self-loosening based on the experiments, and revealed that the self-loosening process can be divided into two distinguishable stages. The first stage is featured by a short and sharp clamping force reduction with no relative rotation between the nut and the bolt. In the second stage, clamping force is gradually reduced as the nut rotates. But, to the second stage self-loosening of bolted joints, it is still not clearly explained how the relative slip occurs between the engaging surfaces of bolt and nut.

Due to the complexity of bolted joints, it is almost impossible to clearly analyze the relaxation mechanism by single experimental methods. And most of the present theoretical researches are conducted based on some unreasonable assumptions to build the self-loosening models. Both of them have excessive limitations. The method of finite element simulation combining theoretical analysis is efficient to solve the problems above, and makes the problem more clearly. In the past, most finite element model of bolted joints were simplified to axially symmetric, not considering the helical thread geometry, which is reasonable to the first stage of self-loosening because of no relative rotation between the bolt and nut. But it is not suitable to study the second stage of self-loosening. This paper establishes a finite element model of bolted joints which consider the helix angle of screw thread. The second stage of self-loosening of bolted joints under different loading conditions is investigated through the theoretical analysis and numerical simulation.

**Numerical Model**

For the common bolted joints of grade 6.8, considering the helix angle of screw thread, the elastic finite element model is established as shown in Fig.1. Because the relative rotation between bolt and nut will occur, the thread can't be simplified as a trapezoidal groove. In this model, two 24mm×24mm×27mm rectangular plates with holes are clamped by a common bolted joint which is grade 6.8. The radius of hole is 6.6mm. Yield strength limit of the material is 480MPa. Strength limit is 600MPa. Elastic modulus \( E = 2.06 \times 10^5 \)Pa. Poisson's ratio \( V = 0.3 \). Hexagon head trapezoidal thread connection is M12x1.75. There are four types of the contacts: 1) between the engaged threads of the bolt and the nut, 2) between the nut and its bearing surface, 3) between the the camped plates, 4) between the bolt head and its bearing surface.

In addition, there is a gasket which is mainly used to produce preload of bolted joints because the gasket will expansion after heating. The coefficient of expansion is \( 1.0 \times 10^{-4}/^\circ \text{C} \). For example, the gasket is respectively heated to 200.5013\(^\circ\) and 257.8797\(^\circ\)C, corresponding to the pre-displacement 0.07mm and 0.09mm. The clamping force is proportional to the
pre-displacement. The selection of expansion coefficient does not have other practical significance. The outer diameter of gasket is 12mm, inner diameter is 6.6mm, and thickness is 3.49mm. During the simulation, the left surface of the lower clamped plate is fixed, while the right surface of the upper clamped plate is subjected to transverse cyclic displacement loading. A full cycle of transverse loading includes four steps: loading from zero position to positive maximum, unloading to zero, loading to negative maximum and returning from negative maximum to zero position.

![Figure 1. a) finite element model of bolted joints b) section of the model c) Threaded engagement surface d) finite element model of each parts.](image)

**The Second Stage of Self-loosening**

Firstly, the friction coefficient of the contact surfaces is set as 0.2, and the pre-displacement is 0.07mm. That is to say, the gasket is heated to 200.5013°C. The magnitude of the transverse cyclic displacement loading is 0.46mm. Simulating of sixteen load cycles, the changes of clamping force and the relative rotation between bolt and nut with the load cycle can be obtained as shown in Fig.2. The horizontal axis is the lateral load cycles and the left vertical axis indicates the change of the clamping force of bolted joints, while the right vertical axis indicates relative rotation angle between the bolt and nut. Due to the complexity of the finite element model of bolted joints, considering the computing time and the much slower relaxation process, the clamping force of bolted joints is set relatively small. As shown in Fig.2, it can be concluded that the second stage of self-loosening of bolted joints is because of the relative rotation between bolt and nut. The angle of relative rotation in each load cycle is approximately identical, which is about 0.0015 rad.
The von Mises stress distribution under the first cyclic of lateral loading is shown as Fig. 3. It can be clearly seen that the stress of bolted joints changes obviously at the process of the transverse load cycle. The larger von Mises stress always occurs in the first engaged thread root or bolt root where is easy to fracture.

Figure 2. Self-loosening process curve of bolted joints.

Figure 3. The von Mises stress contours during a transverse loading cycle.
By analyzing the contact stress change of the contact surfaces in a transverse load cycle, Fig.4(a) can be obtained. The engaging thread surfaces are averagely divided into 80 parts along the helix line, and each of them is about 13.5°. From the changing process of the contact stress in a transverse load cycle, it can be seen that the transverse cycle loading leads to the obviously change of the contact stress, and the local contact stress even reduce to zero, which illustrates that the partial separation occurs between the engaging surfaces.

Fig.4(b) is the contact stress change in the first load step that is the first 1/4 load cycle in which transverse loading is from the origin to the positive maximum. It can be concluded that contact stress changes continuously in the process of the load cycling.

Bolted joints have two obvious changes during the transverse load cycling: 1) the variation of the contact stress between the engaging thread surfaces; 2) lateral micro slip between the engaging thread surfaces. In the simulation above, the amplitude of the relative lateral slip between the bolt and nut is 0.12mm, and the amplitude of the relative lateral slip between the upper clamped part and nut is 0.17mm. What follows in the paper will quantitatively analyze the importance of lateral micro slip between the engaging thread surfaces in the second stage of self-loosening.

**The Influential Factors on the Second Stage of Self-loosening**

**Preload**

Still using the finite element model established above, the friction coefficient of the contact surfaces is set to 0.2, and the pre-displacement is 0.07mm and 0.09mm, respectively. The magnitude of the transverse cyclic displacement loading is 0.46mm. Simulating of eight load cycles, the changes of clamping force with the load cycle can be obtained as shown in Fig.5. It can be concluded that the greater preload will enhance the resisting ability of self-loosening. However, the overlarge preload will easily cause the fatigue failure, so a reasonable preload should be applied in the bolted joints.

**The Amplitude of Transverse Cyclic Displacement Loading**

In this paper, the self-loosening process of bolted joints under the different amplitude of transverse cyclic displacement loading is analyzed. The friction coefficient of the contact surfaces is set to 0.2 and the pre-displacement is 0.07mm. The magnitude of the transverse cyclic displacement loading is 0.46mm and 0.54mm, respectively. The changes of clamping
force with the load cycle can be obtained as shown in Fig.7. The results show that the greater amplitude of the lateral cyclic loading will lead to the faster self-loosening. When the pre-displacement is 0.07mm and the transverse load amplitude is 0.54mm, the average relative slip angle of each cycle is 0.0018rad, which is bigger than 0.0015rad when the transverse load amplitude is 0.46mm.

The Friction Coefficient of the Mating Surface

Here, the self-loosening process of bolted joints under different friction coefficient is investigated. The friction coefficient of the engaging surfaces is set to 0.2 and 0.14, respectively. The pre-displacement is 0.07mm and the magnitude of the transverse cyclic displacement loading is 0.46mm. The changes of clamping force with the load cycle can be obtained as shown in Fig.7.

From Fig.7, it can be seen that the friction coefficient of the mating surfaces has a big influence on the second stage of self-loosening of bolted joints. The smaller friction coefficient of the mating surfaces leads to the quicker loosening. So the bigger friction coefficient of the engaging surfaces can improve the resisting ability of bolted joints to self-loosening.

The friction coefficient of the engaging surfaces has a close relationship with the machining accuracy and surface roughness of bolted joints. Due to the manufacturing reasons, there usually has a gap between the screw threads of bolt and nut. This gap is the necessary condition leading to the lateral micro slip between the engaging thread surfaces of bolt and nut. So the machining accuracy of the thread is very important to improve the resisting ability of bolted joints to self-loosening.
Theoretical Analysis on the Second Stage of Self-loosening

According to the experiments and finite element simulations of self-loosening, it can be obtained that the second stage of self-loosening of bolted joints has two important conditions: 1) the variation of the contact stress between the engaging thread surfaces; 2) lateral micro slip between the engaging thread surfaces. Next, this will be validated by combining the theoretical analysis with quantitative simulation.

Similar to the Junker's simplified model of bolted joints, bolted joints is simplified as the model shown in Fig.8. The lower inclined part is the thread of the bolt whose inclined angle is equal to the Helix angle. Its lower surface is all constrained. The middle inclined part is the thread of the nut. The engaging thread surfaces between these two parts occur a relative slip amplitude of A2 under the transverse displacement cycle loading. The upper part is the clamped plate which contacts with the nut. There also exists a relative slip amplitude of A1 between the nut and the clamped part. The right surface of the clamped part is restrained in the X direction, and the clamped part can freely move in the Y direction. In the simplified model, the weights of all parts are neglected, and the F is the preload in Fig.8. At the static state, the nut has a slip trend under the preload. But the slip of the nut need overcome the friction force coming from the engaging thread surfaces and clamped part. Because of the static self-lock, bolted joints will not slip at the static state. However, under the transverse cycle loading, a small relative slip will occur between the engaging thread surfaces and clamped parts of bolted joints. It changes the connection state of bolted joints, and causes a small relative rotation slip between the bolt and the nut. Finally, the accumulation of the small rotation slip leads to the second stage of self-loosening of bolted joints. For the simplified model of bolted joints shown as Fig.8, the reason of the second stage of self-loosening is quantitatively analyzed by the finite element method.

The pre-displacement is 0.07mm. The friction coefficient of the engaging surfaces is 0.2, and the magnitude of the transverse cyclic displacement loading is 0.46mm. The upper surface of the clamped part is applied an uniform pressure of 24.08MPa as the preload. A1 is 0.17mm and A2 is 0.12mm. Because the clamping force varies in the process of self-loosening of bolted joints, only one transverse load cyclic is simulated. The relative slip displacement of bolt and nut is shown in Fig.9.
There are five load steps, and each load step spends 0.5s. The first step is to add preload, and the next four load steps is a transverse load cycle. The total time is 2.5s. As shown in Fig.9, the relative slip displacement of bolt and nut is 0.036mm. However, the relative slip displacement of bolt and nut in Fig.2 is 0.0138mm after the first transverse load cyclic. This is because in actual operation, the contact stress at different positions and different time are varying, but in the model of Fig.8, the preload is constant. Through the simplified simulation of the bolted joints, it can be seen that the main reason for the second stage of self-loosening of bolted joints is the relative motion between the bolt and the nut, and the relative motion between the contact surfaces of the clamped parts which change the connection state, and make the nut backing-off along the screw under the action of the preload.

During the slip, the clamping force of the bolted joints is gradually reduced which makes the self-loosening more slowly. Moreover, the slow relaxation process will continue, and the bolted joints will be failure due to the fatigue or the lack of preload.

**Conclusion**

This paper establishes the three-dimensional finite element model considering the helix angle of screw thread. Firstly, the second stage of self-loosening process of bolted joints is simulated. Then, the effects of preload, the amplitude of transverse displacement load, and the friction coefficient of the mating surfaces on the second stage of self-loosening process of bolted joints are analyzed. Finally, the mechanism of the second stage of self-loosening of bolted joints by combining theoretical analysis with the finite element simulation is explained. Some conclusions can be drawn as follows:

1. The second stage of self-loosening of bolted joints has two important conditions: a) the variation of the contact pressure between the engaging thread surfaces; b) lateral micro slip between the engaging thread surfaces.

2. The greater preload means better resisting ability of bolted joints to the self-loosening. The greater amplitude of the lateral cyclic loading results in the faster self-loosening. The resisting ability of bolted joints to the self-loosening can be improved by increasing the friction coefficient of the mating surfaces.
(3) The second stage of self-loosening of bolted joints is mainly resulted from the relative motion between the bolt and the nut, and the relative motion between the contact surfaces of the clamped parts. This small relative transverse cyclic slip is the mechanism of second stage of self-loosening of bolted joints.

Acknowledgement

This work was financially supported by the National High-tech Research and Development Program of China (Grant No. 2013CB035706); the National Natural Science Foundation of China (Grant No. 51575425, 51375366, 51139005); and the Fundamental Research Funds for the Central Universities.

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