Analysis of short-term relaxation effects under non-parallel contact

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Abstract: For the typical bolt structure in engineering practice, ensure q235b as the material of the connected component, and the M10 high-strength bolt of 10.9 grade as the fastener. The bolted joint surface geometric deviation of the bolt and the connected component is characterized as the non-parallel of the bolt end face contact. Experimental verification and finite element analysis are performed on the characteristics of short-term relaxation effect under non-parallel contact. Through the axial tightening experiment, the existence of the short-term relaxation effect phenomenon is verified and the relevant material parameters are measured. The static-time axial tightening model is established by using the time strain hardening 7-parameter creep theory model to analyze the tightening performance of bolted joints under non-parallel contact, revealing the variation law of bolt preload force and stress distribution law under non-parallel contact. Provide a reference for the design of the bolted joint and the evaluation of the service performance

Key words: Non-parallel contact, Short-term relaxation effect, Finite element analysis, Bolt preload

1 Introduction

As the first choice for the assembling process, bolted joints are widely used in the automotive industry, new energy, machine toolsand other industries. However, the tightening technology at this stage is not perfect yet. There are many problems in the actual project. In 2001, an F-16 fighter jet of the Royal Netherlands Air Force crashed due to the loosening of the bolted joint under high temperature conditions. A speed control valve bolt of a thermal power plant occurred mixed fracture of fatigue and creep at high temperature after a long time operation. The control of single bolt tightening accuracy is the basic part of the whole tightening process analysis, and is the initial input parameter for subsequent group bolt tightening process design and anti-loose performance analysis. Compared to the regularity of the elastic interaction of the group bolts, the dispersion of the preload force of the single bolt is the main reason of the uncertainty of the whole bolt tightening process.[1-5]

When the bolt is tightened, the bolt is elongated and the connected component is compressed under the axial preload. The deformation of two parts are coordinated to complete the tightening of the bolted joint

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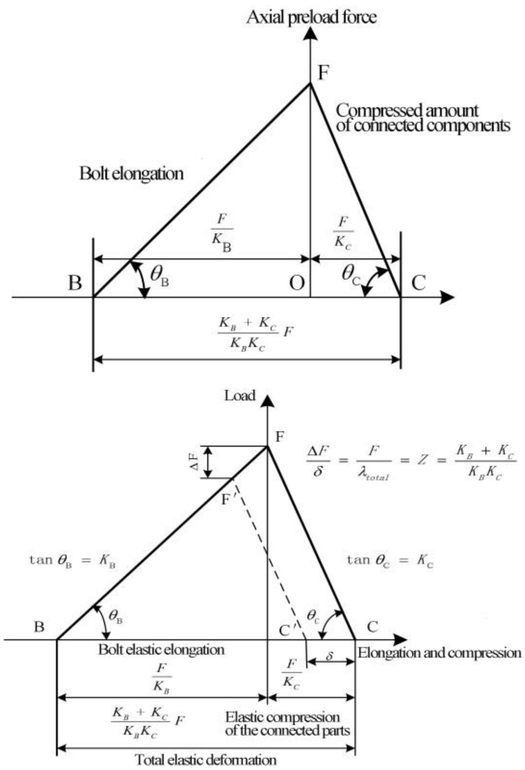

Fig1. Schematic diagram of bolted joint fastening

As long as both the bolt and the connected component are in the elastic state, the ratio of the axial preload of the bolt to the total elastic deformation of the joint is a constant, and irrespective of the axial preload *F*, the ratio is the relaxation coefficient *Z*. The relaxation coefficient Z characterizes the amount of axial preload force reduction of the bolt resulting from the unit settlement of the connecting member and can be considered as the spring constant of the entire bolted joint.

Kulak [6] shows that the BD grade bolt of A325 and A354 materials loses 2 - 11% of the preload force after tightening at once, then other 3.6% reduction in the next 21 days, finally 2% reduction in the next 11.4 years. Fasteners generally relax quickly after initial tightening and then relax at a slower rate. This phenomenon of stress relaxation is called the short-term relaxation effect, which is generally understood as the creep that occurs under decreasing preload force. The phenomenon usually occurs under over-yield conditions, because the plastic deformation of the joint continuously occur causing a significant decrease in the preload force. It will cause further loss of preload force in a long time, thus affecting the bolt tightening accuracy. Using the deformation coordination equation, we can see that the preload force reduction is as follows:

$$\frac{\Delta F}{k_{bolt}}+\frac{\Delta F}{k_{connected-component}}=\frac{F-\Delta F}{k_1}-\frac{F-\Delta F}{k_0} \quad (1)$$

$$\Delta F=\frac{\frac{F}{k_1}-\frac{F}{k_0}}{\frac{1}{k_1}+\frac{1}{k_{bolt}}+\frac{1}{k_{connected-component}}} \quad (2)$$

It can be seen from Fig. 2 that the joint between the fastener and the connected component is plastically deformed continuously under the preload force which is beyond yield limit . As the time of the load-bearing process increases, the plastic deformation gradually increases, and the preload force of the bolted joint gradually decreases, eventually reaching a steady state.

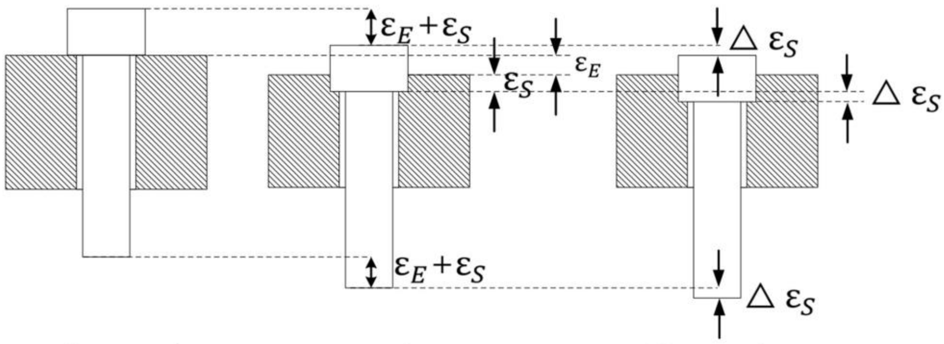

Fig2. Experimental schematic diagram of short-term relaxation effect

Based on the preload force relaxation principle of the bolted joint, the preload force reduction equation can be further analyzed: k0 represents the initial stiffness of the plastic deformation zone and is simplified to the line stiffness, k1 represents the final stiffness of the plastic deformation zone, k bolt represents the bolt stiffness, and k represents the stiffness of the elastic deformation zone . Neglecting 2% preload force reduction , in order to make the material exhibit the short-term relaxation effect characteristics, the time strain hardening model is used to set up the 7-parameter creep connected component model, where C_1>0, C_7>0 . C_1 and C_5 are fitting coefficients, C_2 and C_6 are stress fitting parameters, C_3 is a time fitting parameter, and C_4 and C_7 are fitting coefficients.

$$k_0=\frac{EA}{L} \quad (3)$$

$$k_1-k_0=\frac{F}{\varepsilon_{cr} l} \quad (4)$$

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$$\varepsilon_{\mathrm{cr}} = \varepsilon_{primary} + \varepsilon_{\mathrm{secondary}} = c_1\sigma^{c_2}\frac{1}{c_3+1}t^{c_3+1}e^{(-\frac{c_4}{T_5})} + c_5 t\sigma^{c_6}e^{(-\frac{c_7}{T_5})} \quad (5)$$

At present, scholars at home and abroad have done a lot of research on the stress relaxation characteristics. Jin Hao[7] introduced a reasonable time t* for the residual stress under repeated loading conditions. Zhao Ziyi[8] investigated the effects of different initial stresses on the residual preload force. Yu Zhigang[9] proposed a new experimental method to improve the stress relaxation test device for preload force relaxation. Ganganala et al.[10] studied the effect of load eccentricity on the stress relaxation behavior of bolted joints, and finally pointed out that the strain hardening rate of fastener materials has a great influence on the short-term relaxation effect. Sayed et al.[11] proposed using the nonlinear strain hardening model of materials to study the short-term relaxation effect of bolted joints. Payam et al.[12] studied the short-term relaxation effect under yield tightening, and pointed out that the over-plastic relaxation caused short-term relaxation effects. Cao Tieshan et al.[13] proposed a material analysis model for predicting the long-term creep properties of materials using stress relaxation behavior. Yan Shouhai[14] proposed a composite time-enhanced seven-parameter model to simulate the stress relaxation phenomenon and material creep.

By far,some problems still exist in the research: 1.The control of the single-bolt preload force mainly lacks the theoretical support and analysis model of the system, mainly through empirical formula based on experimental determination. 2. Lack of effective single bolt tightening stress relaxation simulation.

In this text, the short-term relaxation effect verification experiment will be carried out to verify its existence and obtain relevant material parameters. Based on the consistency of the principle of creep and stress relaxation, the static stress relaxation model is established, and the short-term relaxation effect under non-parallel contact is calculated and analyzed.

2 Short-term relaxation under non-parallel contact

2.1 Finite element modeling

In order to analyze the influence of the short-term relaxation effect under non-parallelism , the parameterized finite element modeling of bolted joints was established as the experimental structure. The model consists of a bolt and a connected component. In the text, the short-term relaxation effect between the joint and the bolt end joint surface is mainly considered, so the bolt is simplified as a threadless bolt. The tightening process is carried out by applying the load in the axial direction. The model dimensions are as follows: the thickness of the connected part is L=20mm, the outer diameter is d_m=40mm, the hole diameter d_h=10.5mm, the chamfer diameter r=0.5mm, the diameter of the lower end d_w=14.55mm, the bolt screw diameter d= 9.5mm, the bolt screw length is 20mm. The joint surface of the bolt lower end surface and the upper surface of the connected component is set to be in frictional contact with a friction coefficient of 0.15. A fixed constraint is placed on the lower surface of the connected part and the lower surface of the bolt screw. In order to accurately analyze the influence of the non-parallelism on the short-term relaxation effect, the mesh of the lower surface of the bolt end and the support surface of the connected member is refined by manually controlling the mesh to ensure the convergence of the finite element model.

In terms of applying load, three analysis steps are arranged : 1. The first step is to apply bolt pretension 50000N in 1S, thereby completing the tightening process. 2.The second step starts from the 2S to set the lock command aiming to ensure location removal maintenance of the bolt node. The load-bearing process lasts for 500s. 3.The third step is performed to unload and observe the residual pressure depth of the connected part. The model has 146,720 units, 156,066 nodes in parallel. The geometric structure and finite element structure are as follows:

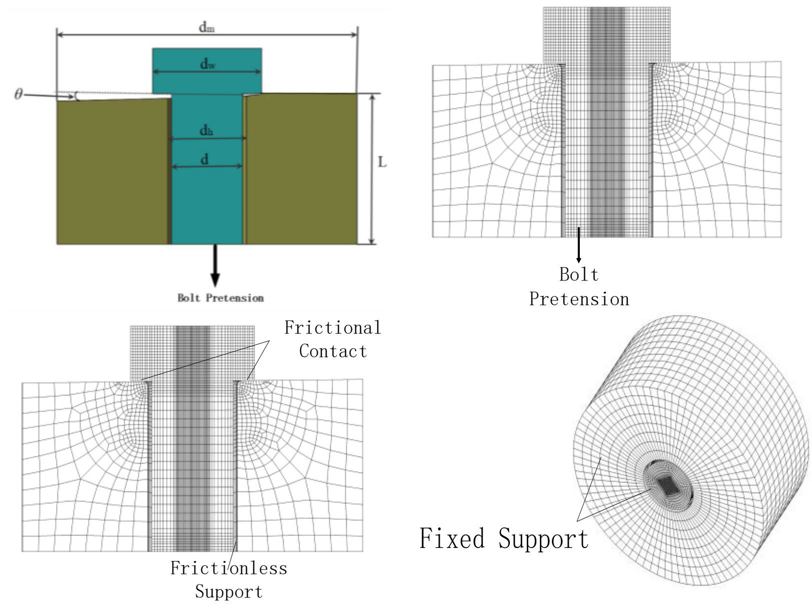

Fig3. Finite element model of bolted joint

In terms of material parameters, the modulus of elasticity of the 10.9 standard bolt is 210 GPa and the Poisson's ratio is 0.3. The material of connected component is q235b: the modulus of elasticity was 210GPa and the Poisson's ratio is 0.3. Using the electric stretching machine, compress the test piece of the same specification to 50000N at the speed of 5000N/S and hold it for 500s. Use the experimental data to find the average value, and select the following ten points to fit the creep characteristics of the material through the finite element. The calculation shows that the fitting curve results have high coincidence with the test data, which proves the set of fitting creep parameters is effective.

Table1. Experimental data of preload relaxation

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t/s	3.9	6.1	13.7	28.5	64.3	103.8	154.9	220.8	322.2	450.4
F/N	49796	49700	49498	49468	49243	49186	49103	49050	48761	48770

Table2. Creep parameter table

C_1	C_2	C_3	C_4	C_5	C_6	C_7
2.5274E-08	1.28	-0.999	1935	1E-14	23.19	40000

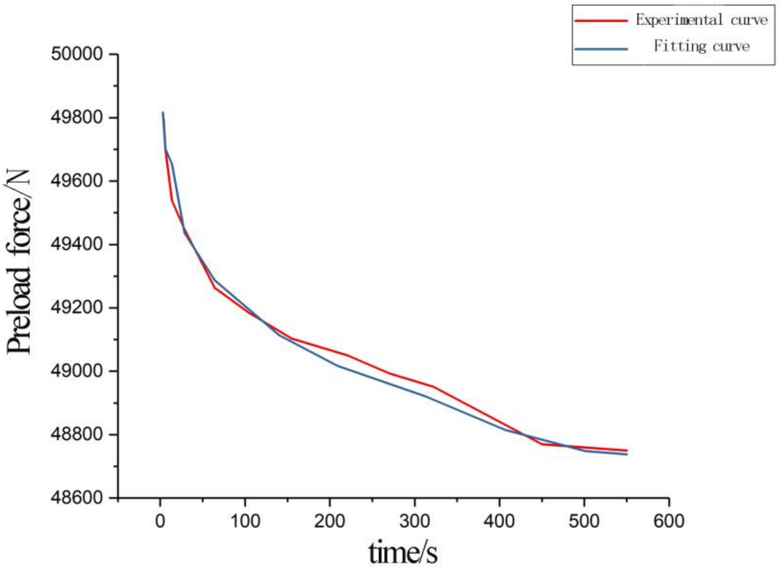

Fig4. Comparison of fitted curve and experimental curve

2.2 Simulation analysis of preload relaxation process

The non-parallel bolt nodes of 0° and 1.8° are selected respectively to analyze the tightening relaxation process. It is found that after the tightening, the internal stress field inside the connected component will have a obvious extension in the 1-100s , so that the connected component will continue to plastically deform. The internal stress field is gradually stabilized during 100-300s , and the plastic deformation is basically finished. The relaxation within 100s after loading is up to 70% of the total amount. This phenomenon indicates that plastic deformation is the main cause of preload relaxation.

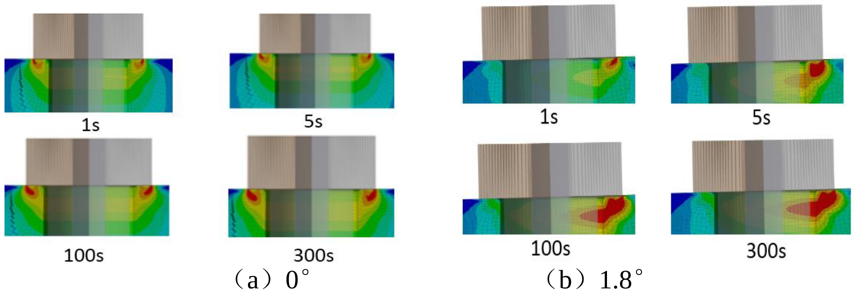

Fig5. Preload force relaxation nephogram

By observing the stress nephogram and residual pressure nephogram at 501s , it can be seen that when the joint surface has non-parallelism, the stress distribution becomes uneven, and the bolted joint is divided into two stages during the tightening process. In the first stage, the screw is bent, and the lower surface of the bolt end gradually forms full contact with the upper surface of the connected component. In the second stage, the axial direction of the screw is elongated, and the preload force of the bolt node is rapidly increased. During the loading process, the stress distribution is asymmetrical due to the bending of the screw. With the increase of non-parallelism, the degree of asymmetry of stress distribution increases gradually, and the degree of asymmetry of residual pressure depth increases gradually, and the phenomenon of stress concentration becomes more and more obvious.

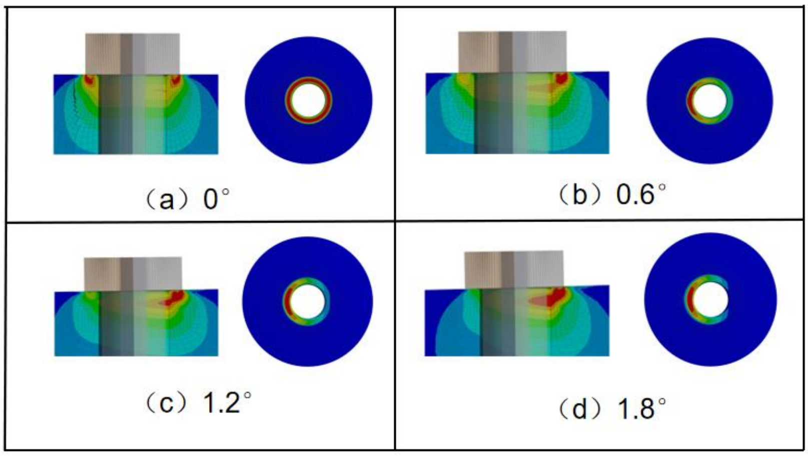

Fig6. 501s stress nephogram and residual pressure nephogram

2.3 Simulation analysis of tightening relaxation results

From the results of the finite element calculation, it can be seen when the non-parallelism increases from 0° to 1.8° , the percentage of preload reduction increases from 2.4% to 8.7%, the maximum stress of the joint increases from 441.4MPa to 483.1MPa and the plastic deformation variable was increased from 0.057 mm to 0.160 mm. Under different non-parallelism, when the loading is completed, the pre-

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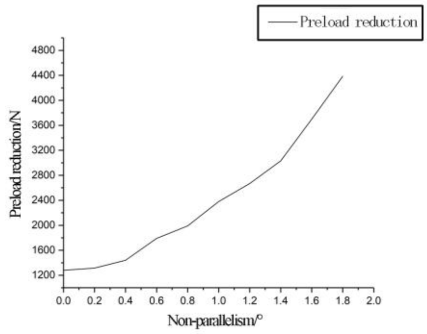
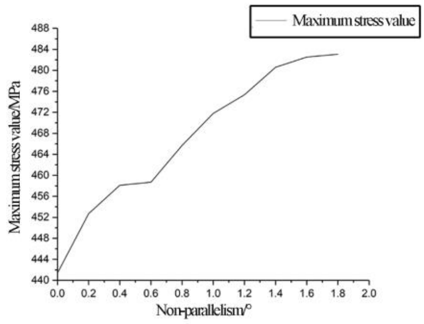
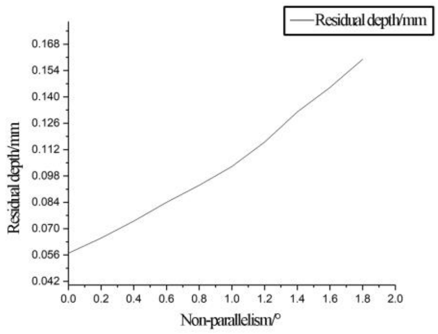
load force of the axial load by the orthogonal decomposition and the average contact stress of the joint surface is similar, but the maximum stress value of the end face of the bolt varies much.With the non-parallelism increases, the phenomenon of stress concentration becomes more and more obvious. Since the parameters in the time strain hardening creep model are all exponential terms, the bolts with stress concentration will produce larger plastic deformation and preload force decreases under the same average stress. Non-parallel deviation will resultin more stress concentration and more obvious short-term relaxation effects during the tightening process.



(a)



（b)



(c)

Fig7. Drop curve of preload, Maximum stress curve of end face,Residual pressure curve

3 Short term relaxation experiment

In this experiment, the axial tightening method is used to tightening the bolt joints. Considering the tensile loading method, when the tensile force is large, the screw may reach the yield limit and cause plastic deformation, which may affects the short-term relaxation effect. Compressed tightening method is adopted as a result. According to the VDI2230 standard, there are two ways to evaluate the short-term relaxation effect. One is to produce 25um residual deformation after being unloaded by the joint, the other is to produce a displacement of 2um in the first 120s of the load-bearing phase. When the compression test method is used, the plastic deformation during the loading process is not easily measured, and it can be equivalent to the tightening force drop amount:

$$G = \frac{\Delta F_D / A_p}{\Delta H / B} \qquad (6)$$

Where G is the elastic modulus of the material, ΛF_D is the preload force reduction, A_P is the effective supporting area, ΔH is the amount of change in the bonding surface pressure, and B is the thickness of the test piece. In this experiment, the elastic modulus of the material is 210GPa, the effective support area is 78.5mm2, and the thickness of the test piece is 20mm. When the preload force reduction reaches to 1696N, the test piece is considered to occur obvious short-term relaxation effect.

The equipment used in this experiment is EZERCON-90183 manual hydraulic press. The material of the connected component is q235b without heat treatment, and the bolt is c M10 polished rod bolt. The specific dimensions are as follows:

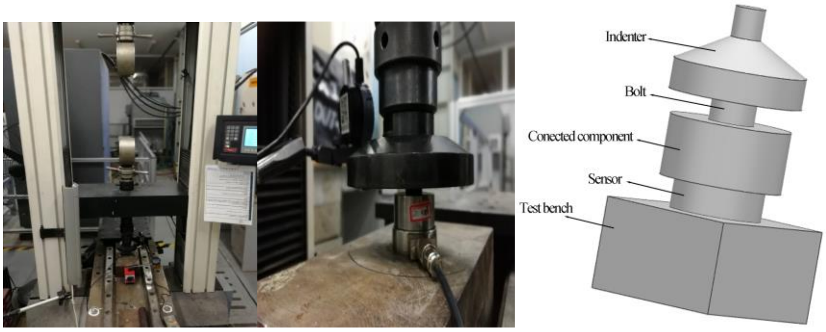


Fig8. Experimental equipment diagram

After the initial loading, the electro-hydraulic machine keeps the load for 120s at every load stage.The non-continuous loading is carried out with a step load of 10000N. The 20t-force sensor reading is used as the output parameter.Through analyzing the preload force reduction at every load stage and the total value of the preload force reduction, the existence of short-term relaxation effects can be verified. The experimental steps are as follows: 1. Install the experimental equipment to complete the system debugging work. 2. Set the compression tightening scheme and perform the force sensor calibration. 3. Turn on the 20t-force sensor and start reading. 4. Start loading to the initial load and keep for 120s. 5. Continue loading to the next stage for 120s. 6. Repeat step 5 until the final load is reached. 7. End the loading, record the experimental data, and analyze the experimental results.

When the bolt is loaded by compression, it can be seen from Fig. 9 that the bolt preload force is reduced by 1300N during the 30,000N load-bearing phase, and the reduction of the next three intervals is decreased by 450N, 300N, 300N respectively. The total preload reduction is 2350N, greater than 1696N, the percentage of decline is 3.9%, which proves that there is a significant short-term relaxation effect.

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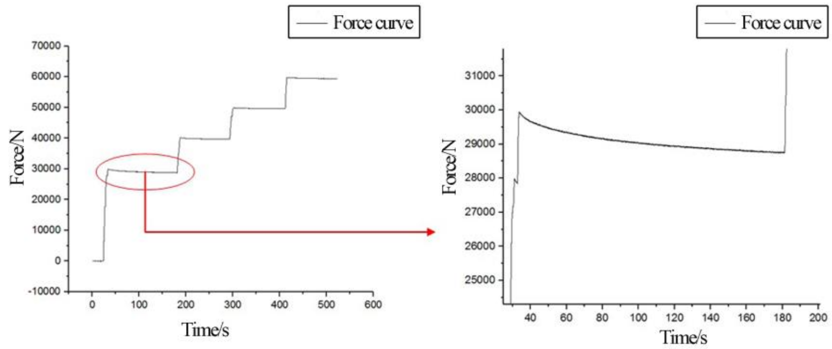

Fig9. Experimental result curve of specimen 1

When the bolt is loaded by compression, it can be seen from Figure 10 that the bolt bolt preload force is reduced by 700N during the 40,000N load-bearing phase, and the reduction of the next three intervals is decreased by 350N, 750N, 500N respectively. The total preload reduction is 2300N, which is greater than 1696N, the percentage of decline is 3.3%, which proves that there is a significant short-term relaxation effect.

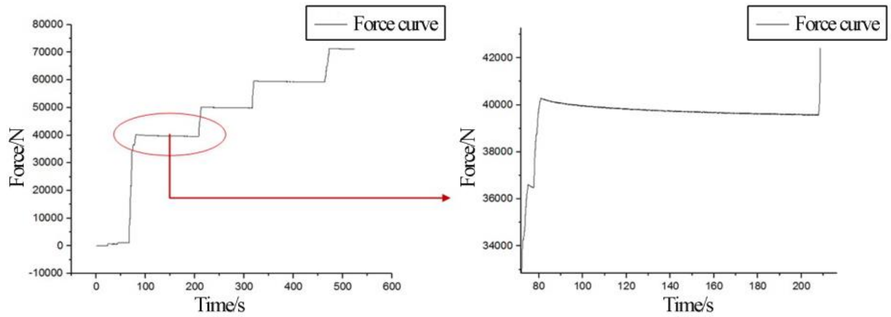

Fig10. Experimental result curve of specimen 2

When the bolt is loaded by compression, it can be seen from Fig. 11 that the bolt preload force is reduced by 900N during the 50000N load-bearing phase, and the reduction of the next two intervals is decreased by 450N and 350N respectively. The total preload reduction is 1700N. The percentage of decline is 2.3%, which proves that there is a more obvious short-term relaxation effect.

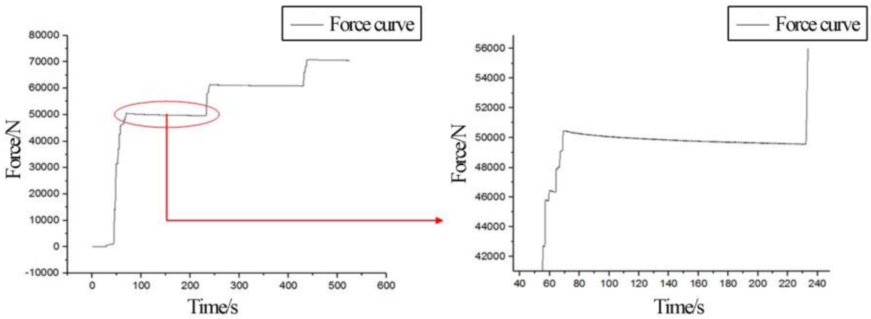

Fig11. Experimental result curve of specimen 3

When the bolt is loaded by compression, it can be seen from Fig. 12 that the bolt preload force is reduced by 1100N during the 60,000N load-bearing phase, and the reduction of the next two intervals is decreased by 450N respectively. The total pre-load reduction is 15500N. The percentage of decline is 2.2%, which proves that there is a more obvious short-term relaxation effect.

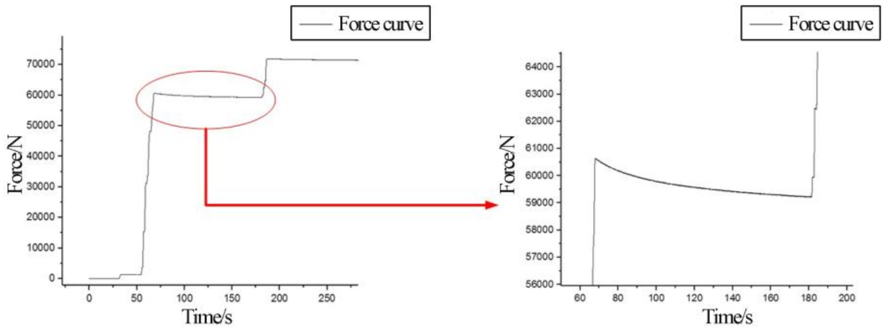

Fig12. Experimental result curve of specimen 4

Applying an axial load of 50,000 N to the connected component, keeping the load for 500s, recording the preload force reduction process, and obtaining the average value of ten sets of test pieces, as shown in Table 1.

In summary, during the loading process, under different loading schemes, there is always a preload force reduction of at least 2%-3% in the load-bearing phase after loading without considering the thread. In actual engineering applications, with the further increase of the load-keeping time and the load impact under the working condition, the preload force reduction will decrease more obviously, which means the short-term relaxation effect will becoming more apparent. Since the experiment selected 45 steel which is widely used in practical engineering applications as the connected component, it can prove the widespread existence of short-term relaxation effect and the important influence of the upper bonding surface in the short-term relaxation effect.

4 Conclusion

The q235b is selected as the material of the connected component. The connected component is axially compressed without considering the thread. By analyzing the experimental phenomenon, it can be seen that under different loading conditions, the bolted joints will have a relatively obvious preload force reduction, which proves that the short-term relaxation effect is widespread in engineering practice, and proves that the upper combined surface is over-substituted. Tightening will continuously occur plastic deformation, which has a significant impact on the preload reduction.

The experimental data was substituted into the time strain hardening creep model.

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The relevant material parameters are obtained by fitting, and the finite element simulation model is established. It can be seen that when there is a non-parallel angle, the lower surface of the bolt end gradually conforms to the upper surface of the connected member during the tightening process. Compared with the parallel state, the stress concentration phenomenon on the side of the screw bending direction is very obvious in the non-parallel contact state. The stress concentration phenomenon becomes more and more obvious as the non-parallelism increases. With the increase, the short-term relaxation effect is also more pronounced. Effectively decreasing the stress concentration phenomenon can reduce the short-term relaxation effect and improve the single-bolt tightening precision. This finding is of great significance for subsequent research.

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Reference

1. Xu F, et al. Modeling of the temperature-related two-stage creep aging for Al-Zn-Mg-Cu aluminum alloy[J]. ***Rare Metal Materials & Engineering***, 2018, 47(2):496-502.
2. Marc-Antoine B, Kamran B. Analytical lump model for the nonlinear dynamic response of bolted flanges in aero-engine casings[J]. ***Mechanical Systems and Signal Processing***, 2019, 115:14-28.
3. Zhang M, et al. The roles of thread wear on self-loosening behavior of bolted joints under transverse cyclic loading[J]. ***Wear***, 2017:S0043164817310670.
4. Zhu L, et al. On controlling preload and estimating anti-loosening performance in threaded fasteners based on accurate contact modeling[J]. ***Tribology International***, 2016, 95:181-191.
5. Nerilli F , Vairo G . Progressive damage in composite bolted joints via a computational micromechanical approach[J]. ***Composites Part B: Engineering***, 2017, 111:357-371.
6. Kulak GL, Fisher JW and Struik JH. Guide to design criteria for bolted and riveted joints. Chicago:***AISC***, 2001
7. Wei N, Jin Y. Research on metal stress relaxation at high-temperature [J]. ***Chinese Mechanical Strength***, 1997(3):57-60.
8. Zhao Z, Li P. Study on stress relaxation behavior of new type bolt steel[J]. ***Hot Working Technology***, 2017(04):119-121.
9. Yu Z, Yang J, Zhang Y. Experimental study on stress relaxation of bolts at room temperature [J]. ***Journal of Solid Rocket Technology***, 1999, 22(3):55-58.
10. Nassar S A , Ganganala M. Effect of separating load eccentricity on the clamp load loss in a bolted joint using a strain hardening model[J]. ***Journal of Pressure Vessel Technology***, 2011, 133(2):021206.

11. Nassar S A, Matin P H. Nonlinear strain hardening model for predicting clamp load loss in bolted joints[J]. ***Journal of Mechanical Design***, 2006, 128(6):1328-1336.
12. Nassar S A, Matin P H. Fastener tightening beyond yield[C]// ***ASME/JSME 2004 Pressure Vessels and Piping Conference***. 2004:29-40.
13. Cao T. Research and application of relationshiop between high-temperature stress Relaxation and Creep of Heat Resistant Steel[D]. 2016.
14. Yan S. Experimental study on creep behavior in steel at elevated temperature [D]. 2015.

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