

Experimental study on high strength bolt pre-tightening force of friction energy dissipation device

MEI Xiao ^{1, a}, CHEN Guo ^{2, b} and LIU Hai-yang ^{3, c}

Logistics Engineering College, Shanghai Maritime University, Shanghai, 201306, China

^aemail: xiaomei@shmtu.edu.cn, ^bemail: guochen10@126.com, ^cemail: hylu@shmtu.edu.cn

Keywords: High-strength Bolts; Turn-nut Method; Friction-energy-dissipation Device;

Abstract. The pre-tightening force experiment to high-strength bolts of friction-energy-dissipation device were implemented by the turn-nut method and then obtained the linear scale between pre-tightening force and angle of rotation by analyzing the data. This provides a reference for the measurement of bolt pre-tightening force. At the same time computed the stiffness of connection attachments and connected members by Workbench and the pre-tightening force of bolts with related parameters. The comparative results with the experimental data can make a reference for applications of high-strength bolts connection in friction-energy-dissipation devices.

Introduction

Friction-energy-dissipation device is characterized by simple structure, transparent energy dissipation mechanism and stable performance. It can provide greater additional damping and additional stiffness. The magnitude of load, loading frequency and load cycles have little influence on its energy dissipation. The basic mechanism is that composite components and friction plate connect by a bolt, produce sliding friction under a certain pre-tightening force, use sliding friction to make energy consumption and then protect the structure[1]. Thus, bolt connection of friction energy dissipation device has a very high requirement on the pre-tightening force accuracy. A large number of experiments and experience proved that higher pre-tightening force is beneficial to the reliability of the connection, but overtoping it may lead to the failure of connection in case of improper control or accidental overload. In order to keep the pre-tightening force needed and avoid overload of screw thread, the pre-tightening force must be controlled when the important thread connections are assembling.

The torque method and the angle method are the common methods in controlling and monitoring pre-tightening numerical. Lin Hu demonstrated that the angle tightening technology has wide application in the engine bolt joint, which is based on the mechanism of screw thread joint technology and production practice [2]. Sun Qinli and Li Chen studied the cylinder head bolt connection and the steel structure high strength bolt connection respectively by using the angle method, and got the similar relationship between the angle and pre-tightening force[3][4]. But none of them has simulated the experiment by finite analysis element and then make a comparison with it. MICHAEL J GILROY introduced the factors influencing the relationship of the angle of rotation and pre-tightening force [5].

Torque coefficient changes result in great error of the bolt pre-tightening force. So considering pre-tightening force error and costs and other factors, in this paper, we use the angle method and the finite element analysis combined with the formula to calculate the bolt pre-tightening force. Finally, the calculated and experimental results are compared and analyzed.

The experimental principle and devices

The torque method, which controls the pre-tightening force of connected members by the torque value displayed on torque wrench, is operationally simple and intuitive. Tightening torque M :

$$M = KF_0 D \times 10^{-3} . \quad (1)$$

In the type: F_0 is pre-tightening force; K is torque coefficient; D is nominal diameter.

In the process of experienced design, the value of torque coefficient K is generally taken to be 0.2. But, the value of K is not a constant. It fluctuates in the range of 0.1~0.3 with the change of such variables as the finish of threaded surface and connected members, the status of lubricating, the speed of screwing, the tool of screwing and the temperature change with repeated tightening and so on.

From the point of thread kinematics, the axial displacement that generated by the rotation of the nut is as the formula below:

$$S = P\theta/360^\circ . \quad (2)$$

In the type: θ is the angle of rotation; P is the pitch of screw; S is axial displacement;

In fact, when the rotation of the nut compacts the connected members, the connected members is condensed on the axial direction, and the bolt is extended, the stress and deformation principle is equivalent to two springs in series with different stiffness, as shown in Figure 1.

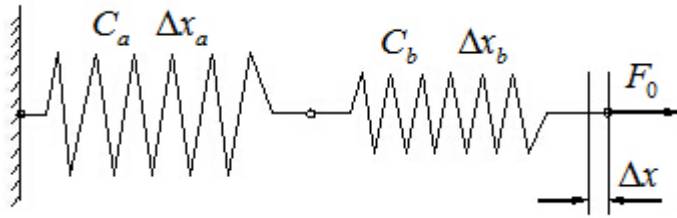


Fig.1 Series-connected spring system



Fig.2 The experimental device

The stiffness of the series-connected spring system is $C = C_a C_b / (C_a + C_b)$, the pre-tightening force is:

$$F_0 = CS = C_a C_b P\theta / [360(C_a + C_b)] . \quad (3)$$

In the type: C is the stiffness of the system; C_a is the stiffness of part a; C_b is the stiffness of part b; F_0 is pre-tightening force;

The formula shows that there is a linear relationship between the pre-tightening force F_0 and θ , which stands for the angle of the rotation. Formula (3) shows that the pre-tightening force is related to the stiffness of the bolt and connected members, and has nothing to do with the friction factor [7].

In the experiment, we measure high-strength bolts of strength class 8.8 M36x270mm used in friction-energy-dissipation device and get the data that the pitch of screw $P=4\text{mm}$, effective cross-sectional area of screw $A_e=816.7\text{mm}^2$. The pre-tension of M36 high-strength bolts is 366kN defined in literature [6]. The experimental device is shown in Figure 2. This experiment in the test road bridge adopts the temperature compensation method of half bridge, for avoiding the influence which temperature change produce to measure result.

Screwing the bolts is divided into two steps, initial tightening and final tightening. Initial tightening torque is 300N.m. The purpose of it is eliminating the gap between the connection attachments. Then, we use dial torque wrench and torque multiplier to load and record the reading of static strain gauge and the angle turned of nut(mark the end of the initial tightening as the starting point of the turn-nut), until the end of the final tightening. According to the Formula (1), the pre-tightening force initial tightening produces is 41.67kN.

Table 1 is the experimental data of four bolts loaded under the angle method.

Table 1 The experimental data under the angle method

Data1		Data2		Data3		Data4	
Angle [°]	Pre-tightening force[kN]	Angle [°]	Pre-tightening force[kN]	Angle [°]	Pre-tightening force[kN]	Angle [°]	Pre-tightening force[kN]
0	61.8918	0	36.2081	0	48.2775	0	36.827
5	75.0232	11	51.1742	14	71.6438	10	54.5536
17	117.411	22	76.2785	35	118.569	19	89.1203
29	164.723	30	105.535	44	156.226	29	124.556
40	219.856	39	135.370	54	195.041	37	180.654
48	258.767	50	182.103	63	238.491	45	247.471
60	314.479	60	221.594	70	272.478	53	273.733
60	318.245	71	278.561	77	299.514	68	291.403
—	—	77	308.107	80	312.065	74	312.742

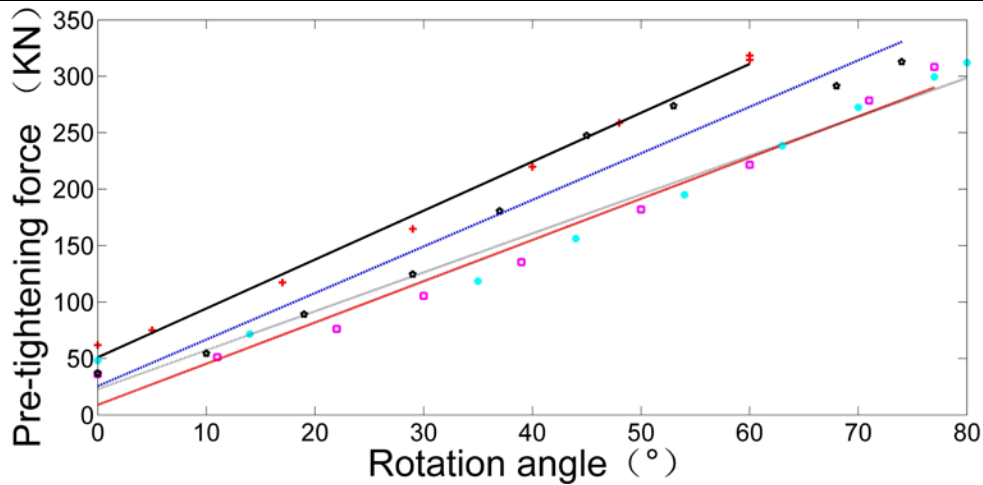


Fig.3 The fitting curve of angle and pre-tightening force

The connection between angle of rotation and pre-tightening force is shown in Figure 3 by using Matlab to fit the data from Table 1. There are linear relationships between each pair of pre-tightening force and the angle of rotation which have similar slopes. In other word, the incremental ratio of each pair of pre-tightening force and rotation angle are similar (increment of pre-tightening force under one degree of rotation). The ratios of four groups are 4.3316kN/°, 3.6503kN/°, 3.4457kN/°, 4.1223kN/°, the average is 3.8875kN/°. The differences of initial pre-tightening force are caused by the unstable torque coefficient.

Finite element simulation

The experimental model is modeled and assembled by SolidWorks, and the bolt lever is simplified as the cylinder whose cross-sectional area is $A\varepsilon$, ignoring the chamfer and fillet that had little impact on the results. At first, the model is imported into Ansys Workbench. Then depending on the experience, the bolt preload mainly exerts on the first five ring thread. In the range of the first five ring thread, Stud was carried Imprint Face treatment to easily exert load and extraction data. Finite element model is shown in Figure 4. The material parameters of every part are shown in table 2.

Table 2 The material parameters of every part

Names of Parts	Material	Elastic modulus[GPa]	Poisson's ratio
Bolt	35CrMoA	203	0.3
Screw nut	45	210	0.3
Washer	45	210	0.3
Plate	Q345	210	0.3
Sleeve	Q235	205	0.3

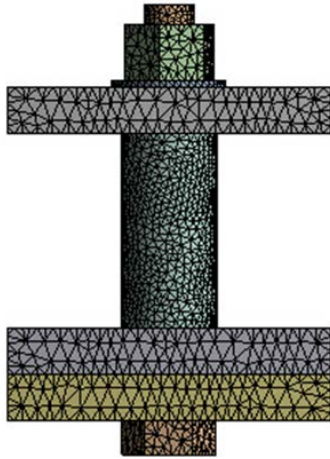


Fig.4 Finite element model

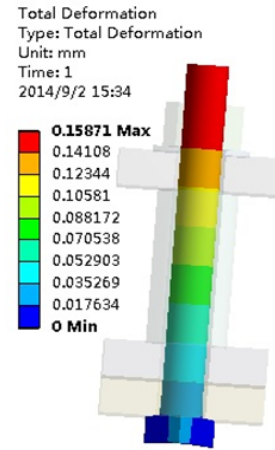
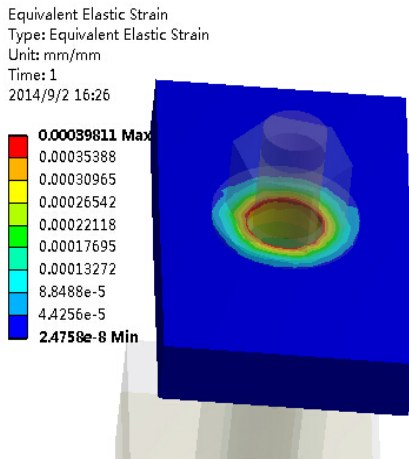


Fig.5 The deformation of connector

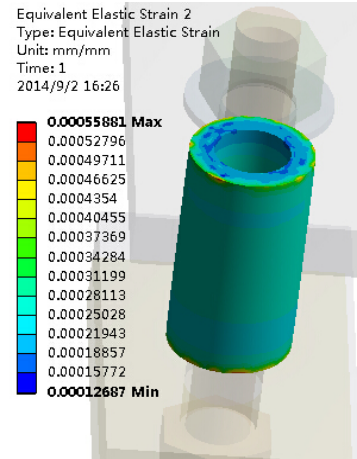
Contact between the nut and stud are setted as Bonded, and the rest of the contact parts are set to Frictional. The friction factor is 0.2. The tetrahedral element is used to mesh the model. According to experimental requirements, the hexagonal bolt head two symmetry planes is fixed, respectively analyzing connector and clamped members: (1) Tension is applied in the connecting piece mark surface, $F=10^5\text{N}$, bolt axial direction.(2) Bolt pretension is exerted in the studs face, $F=10^5\text{N}$.

Under the force, connector deformation of the stud in the axial direction are shown in Figure 5, the amount of deformation $\Delta x_a=0.157\text{mm}$ (mean), the stiffness of connector

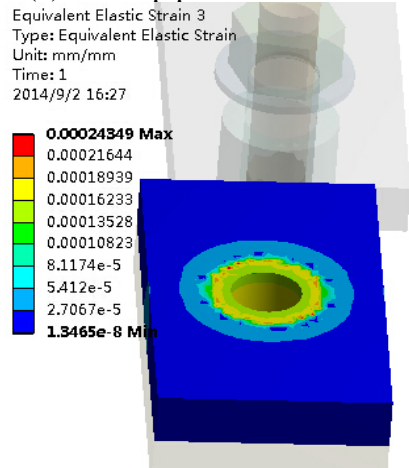
$$C_a = \frac{F}{\Delta x_a} = \frac{100000}{0.157} = 6.369 \times 10^5 \text{ N/mm.}$$



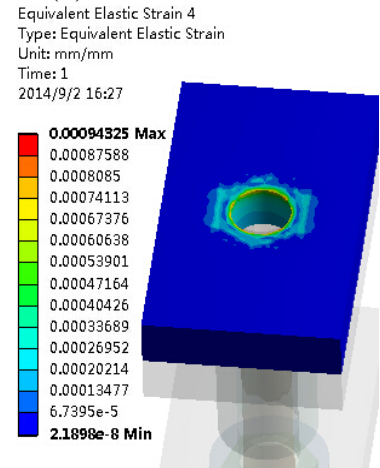
(a) The top plate strain



(b) Sleeve strain



(c) The middle plate strain



(d) The bottom plate strain

Fig.6 Strain distributions

Under the action of pre-tightening force, the amount of deformation of clamped members is equal to the strain multiplied by their respective thickness. The total deformation of the clamped members is equal to the sum of the amount of deformation of each component, $\Delta x_b = 0.1179\text{mm}$, member stiffness $C_b = \frac{F}{\Delta x_b} = \frac{100000}{0.1179} = 8.48 \times 10^5 \text{ N/mm}$. Strain distributions is shown in Figure 6.

According to the formula (3) $\frac{C_a C_b}{C_a + C_b} \times \frac{P}{360} = 4.0411 \text{ kN/}^\circ$, that incremental ratio of the pre-tightening force obtained depending on the stiffness of connector and the stiffness of the clamped members and the rotation angle is 4.0411kN/° by FEM, while incremental ratio is 3.8875kN/° by the experiment, and both the relative error is only 3.95%. Due to the finite element model simplification, it is considered that the error between the two is reasonable.

Conclusions and recommendations

Through contrasting the experiment and finite element simulation, the results show that:

(1) On the premise that the bolts are under elastic region, when we use angle method to tighten the bolt, the final pre-tightening force deviation is produced by the initial tightening, and the deviation is transferred to a final tightening equally.

(2) According to the formula, using finite element method to calculate the stiffness of connector and the clamped members, it can be used as the calculation method of this kind of bolt pre-tightening force in engineering design to replace part of the measurement test.

We tried to use the finite element analysis software to simulate the actual bolt tightening process. However, there is a complex contact surface between bolt and nut, which increase the difficulty of the contact analysis. Therefore, the result is not ideal. We hope that we will improve the model and calculation method in the future study, and we can make the performance of high strength bolt pre-tightening process research perfect in the finite element simulation.

Acknowledgement

This research was sponsored by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry.

References

- [1] Tang Tongbi, Zhou Yun, Yang Bo. Types and performance of friction dampers and their engineering applications [J]. World Earthquake Engineering, 2008, 24 (1):47-55.
- [2] Lin Hu and so on. Comparison between torque method and angle method in bolt assembly technology [J]. Automobile Technology & Material, 2003 (9):41-44.
- [3] Sun Qianli and so on. Establishment of torque-angle tightening process of cylinder head bolts of diesel engine [J]. Automobile Technology & Material, 2003(11):33-35.
- [4] Li Chen, Zhu Yongjun, Hou Zhaoxin. Theoretical and testing study on tightening behavior of high-strength bolts and turn-of-the-nut method [J]. Building Structure, 2013, 43(S1):448-452.
- [5] MICHAEL J GILROY, KARL H FRANK. Tightening of high-strength metric bolts [M]. TX-97 /2958-1F, 1997.
- [6] GB/T3811-2008, Design rules for cranes[S].
- [7] Zhu Zhengde, Lin Hu. Comparison and application research of torque method and angle method in bolt assembly technology [J]. Design & Manufacture of Diesel Engine, 2005, 14(2):40-43.