Mechanical Behaviors of Bolted Joint during Tightening Using Torque Control*

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In the tightening process of a bolted joint using torque control, the effects of friction on axial tension of bolt and torque is an issue of great interest. In this study, the mechanical behaviors of a bolted joint during tightening, such as variations of axial tension and torque, are investigated both experimentally and numerically. Hence, friction coefficients on pressure flank of screw thread and the nut loaded surface are estimated by measuring the total torque applied to nut, axial tension and thread friction torque, and compared with variations of axial tension and torque. The validity of the finite element approach proposed here for evaluating changes in torque and axial tension is ascertained by comparing the numerical results to the experimental ones. It is also shown that the size of grip length influences, to some extent, the reduction rates of torque and axial tension.

Key Words: Fixing Element, Contact Problem, Elasticity, Finite Element Method, Friction

1. Introduction

In tightening structural members using bolt and nut, a torque control method is widely used except for bolts with large nominal diameter. Although friction coefficients on pressure flank of screw thread and nut loaded surface have dominant effects on the accuracy of bolt axial tension so obtained, it is extremely difficult to estimate these coefficients by taking the effects of lubricating conditions and roughness of contact surfaces and material properties of fastened plate⁽¹⁾. It is also known that thread friction torque decreases and the axial tension of bolt is slightly reduced when releasing the tightening torque after the completion of the tightening operation^{(2),(3)}. Thus, it is significantly important to clarify the above mentioned mechanical behaviors, for the purpose of more effective applications of a torque control method.

In this study, the phenomena of the reductions in thread friction torque and axial tension, which occur just after releasing the tightening torque applied to nut with a spanner, are investigated by continuously measuring axial tension, torque and coefficients of friction on pressure flank of screw thread and nut loaded surface. Consequently, the mutual relationships between those factors are comprehensively estimated. Furthermore, a finite element approach, which can deal with the mechanical behaviors stated above as three-dimensional elastic contact problem, is proposed and numerical values so obtained are compared to experimental ones.

Nomenclature

- b, n, f: subscripts for bolt, nut and fastened plate
- d : nominal diameter of bolt
- d_n : equivalent friction diameter of nut loaded surface
- d_2 : pitch diameter of bolt
- F_b : axial tension of bolt
- i in μ_{ij} : subscript identifying contact surface
- j in μ_{ij} : subscript identifying the process of tightening

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- $[K_b], [K_n], [K_f]$: stiffness matrices
 $[K_{fc1}], [K_{clf}], [K_{cl}], \text{etc.}$: matrices relevant to contact conditions
 L_f : grip length
 L_1 : nut thickness
 p : thread pitch
 Q : nodal force
 R_i : equivalent contact force
 T_t : tightening torque applied to nut
 T_1 : thread friction torque
 T_2 : nut friction torque
 u : displacement of node
 U_{t1}, U_{t2} : total strain energy stored in bolt
 ΔU_{Fb} : decrease in strain energy generated by F_b
 ΔU_t : decrease in total strain energy
 ΔU_{T1} : decrease in strain energy generated by T_1
 α : half angle of thread
 β : lead angle
 $\gamma_1, \gamma_2, \gamma_3$: rates of change in axial tension and each torque
 δ_i : initial discrepancy at each contact surface
 μ_1 : friction coefficient on pressure flank of screw thread
 μ_2 : friction coefficient on nut loaded surface
 μ_{ij} : mean values of friction coefficients
 ξ_1, ξ_2 : rates of change in friction coefficients

2. Experimental Procedures

Metric bolts with coarse thread of M 16 are used here. To assess the effects of grip length L_f , five types of bolts with different grip length, such as $L_f = 35, 60, 85, 110, 135$ mm, are prepared. For each grip length two bolts are used, and the measurements are repeated five times for each bolt. The data obtained in the fifth experiment are adopted, because the scatter involved rapidly decreases while repeating the experiments. Each contact surface is in dry condition and the mating surfaces between fastened plates are

Fig. 1 Configuration of clamped cylinder

polished with No. 100 sandpaper every fifth measurement. In case of $L_f = 35$ mm, eight bolts are employed for both dry and lubricated conditions, where grease is applied to the nut loaded surface. The fastened plates made of S 55 C are machined for corresponding grip length, as illustrated in Fig. 1. Although fastened plates are usually composed of two or more parts, one body cylindrical model is employed here because the effects of the contact surface of plate are considered to be negligible, except for tightening thin plates. Two grooves are machined at the bottom the cylinder in order to take out strain gauges and constrain the rotation of bolt head when applying torque. The cylinder has two flat planes on its lateral surface, which are parallel to each other, to be fixed with a vice.

The tightening torque T_t is applied to the outer surface of hexagon nut with a spanner, and it is gradually increased until its value reaches the specified amount of 104.5 [Nm], and then the torque is progressively released. In order to compare the variations of friction coefficients, torque and axial tension with respect to time, three factors, such as axial tension of bolt F_b , thread friction torque T_1 and tightening torque T_t , are measured simultaneously. F_b and T_1 are directly measured with strain gauges attached to the bolt. The total tightening torque T_t is measured with strain gauges attached to the spanner, which is especially designed for the measurement of bending moment applied. Nut friction torque T_2 is simply calculated following the equation of $T_2 = T_t - T_1$. Dynamic strain amplifier is used, and the data so obtained are continuously recorded through oscillographic recorder and can be evaluated at the minimum time interval of 0.02 second.

3. Experimental Results

3.1 Variations of torque and axial tension with time

Figure 2 shows how each torque component, such as T_1 , T_2 and T_t , changes with respect to time during the tightening operation, where the length of arrow indicates the magnitude of torque. The relationship of $T_t = T_1 + T_2$ is assumed to hold throughout the whole tightening process. It is observed that each torque component begins decreasing when the magnitude of T_t reaches the prescribed value and the spanner is removed. Nut friction torque T_2 decreases to be zero and it finally has reversed sign. On the completion of tightening process, the amount of T_t is zero, while T_1 and T_2 satisfies the equation of $T_2 = -T_1$. The corresponding experimental results for bolt axial tension and each torque component are given in Fig. 3, where "time zero" in the abscissa indicates the starting point

Fig. 2 Releasing process of tightening torque

(a) $L_f = 35$ mm (b) $L_f = 135$ mm

Fig. 3 Variations in torque and axial force

(a) $L_f = 35$ mm (b) $L_f = 135$ mm

Fig. 4 Variations in axial force and friction coefficient

of tightening operation, e.g., for the case of $L_f = 35$ mm the applied torque was released in 8.5 seconds after the tightening operation starts. Similar tendencies are observed for $L_f = 35$ and 135 mm.

3.2 Axial tension and friction coefficient on contact surface

Measuring bolt axial tension F_b , total tightening torque T_t and thread friction torque T_1 , nut friction torque T_2 can be calculated, and then friction coefficients on pressure flank of screw thread μ_1 and the nut loaded surface μ_2 are obtained by the following equation, respectively⁽⁴⁾.

$$\mu_1 = \tan \left\{ \tan^{-1} \left(\frac{2T}{d_2 F_b} \right) - \beta \right\} \cos \alpha' \quad (1)$$

$$\mu_2 = \frac{2T_2}{d_n F_b}$$

where β , d_2 and α' are lead angle, pitch diameter and

half angle of thread in the plane perpendicular to helix, respectively. d_n is equivalent friction diameter of nut loaded surface, which is usually said to be 1.3 times a nominal diameter d ⁽⁴⁾. In this paper, however, numerical results of $d_n = (1.32 - 1.35)d$ predicted by FEM are adopted, where coefficients of friction determined experimentally are incorporated into the numerical calculation.

Figure 4 indicates variations of μ_1 , μ_2 and F_b in the dry condition during the whole process of tightening operation, in case of grip length being 35 mm and 135 mm. In the early stage of tightening operation, coefficients of friction are rather high and thus the rate of increase in F_b is low due to insufficient rubbing of contact surfaces. As the tightening torque is increased, friction coefficients approaches to be constant values. Friction coefficients, then, start to

Fig. 5 Variations in axial force and friction coefficients

decrease when the specified torque indicated by dashed line is attained and the spanner is removed. Especially, μ_2 has reversed sign after experiencing zero. A slight increase in axial tension F_b , however, is observed after releasing the tightening torque. It is predicted to be primarily caused by the releasing of strain energy stored in bolt. The reduction in friction coefficients observed here is supposed to be due to anti-clockwise rotation of nut, shown in Fig. 2. In Fig. 4, μ_{ij} are mean values of friction coefficients, where subscripts $i=1,2$ represent pressure flank of screw thread and nut loaded surface, respectively, while $j=1,2$ indicate the situations of before and after the release of tightening torque. Similar results are produced for different grip length. In the case of $L_f=35$ mm, where some grease is applied to the nut loaded surface, variations in coefficients of friction are generally small.

Figure 5 illustrates how each data shown in Fig. 4 varies with time after removing the tightening torque, in which each value is given by the first-order time derivative. It appears, then, that when $d\mu_2/dt$ reaches the maximum value, the amount of dF_b/dt turns into negative value and the axial tension F_b begins decreasing. It is, therefore, concluded that the reduction in axial tension is largely influenced by the friction coefficient μ_2 on nut loaded surface.

4. Numerical Analysis

4.1 Global stiffness equation

In this section, Finite Element Method is applied to analyze the rates of change in bolt axial tension F_b , thread friction torque T_1 and nut friction torque T_2 , designated by γ_1 , γ_2 and γ_3 , each of which is defined as the amount at the completion of tightening divided by that before the removal of spanner. Numerical models are consisting of three elastic bodies, such as bolt, nut and fastened plate, with three contact surfaces of pressure flank of thread, nut loaded surface and bearing surface of bolt head⁽⁵⁾.

The numerical method proposed here is based on Okamoto's method⁽⁶⁾, which is intended for solving two bodies with one contact surface, and it is extended to be appropriate for three bodies with three contact surfaces. The global stiffness equation to be solved is as follows:

$$\begin{bmatrix} K_b & 0 & 0 & K_{bc1} & 0 & K_{bc3} \\ 0 & K_n & 0 & K_{nc1} & K_{nc2} & 0 \\ 0 & 0 & K_f & 0 & K_{fc2} & K_{fc3} \\ K_{C1b} & K_{C1n} & 0 & K_{C1} & 0 & 0 \\ 0 & K_{C2n} & K_{C2f} & 0 & K_{C2} & 0 \\ K_{C3b} & 0 & K_{C3f} & 0 & 0 & K_{C3} \end{bmatrix} \begin{Bmatrix} u_b \\ u_n \\ u_f \\ R_1 \\ R_2 \\ R_3 \end{Bmatrix} = \begin{Bmatrix} Q_b \\ Q_n \\ Q_f \\ \delta_1 \\ \delta_2 \\ \delta_3 \end{Bmatrix} \quad (2)$$

where $[K_b]$, $[K_n]$ and $[K_f]$ are stiffness matrices for bolt, nut and fastened plate, and other matrices are associated with contact conditions. Displacement of node and equivalent nodal force are expressed by u and Q , where subscripts b , n and f are used for the terms relevant to bolt, nut and fastened plate. δ_i and R_i are initial discrepancy and equivalent contact force, where subscript i denotes each contact surface.

4.2 Analytical conditions

Tightening process using torque control method reduces to three dimensional problem. By taking the effects of lead angle into consideration only for the nodes on pressure flank, three dimensional analysis involved can be executed using two dimensional mesh pattern, with each node having three degrees of freedom⁽⁷⁾. The whole tightening process is evaluated in two steps, where the situations before and after the removal of tightening torque are analyzed separately. First, the tightening torque is applied as circumferential distributed loads at the outer surface of nut with cylindrical shape. In the next step, so obtained strains of each part of the joint are given as initial strains to analyze how much rates of torque and bolt axial tension are released when the tightening process is completed. Coefficients of friction used here are referenced to those represented by thin lines in Fig. 4, where μ_{11} and μ_{21} are values concerning the first step,

and μ_{12} and μ_{22} are used in the second step. Coefficients of friction are assumed to be identical both in radial and circumferential directions.

4.3 Contact conditions during tightening process

Five types of contact conditions are treated here, such as (1) separation, (2) slip, (3) slip in radial direction and stick in circumferential direction, (4) slip in circumferential direction and stick in radial direction and (5) stick. It is considered that while applying torque, there always occurs slip in the circumferential direction at each contact surface, as long as the mating surfaces remain in contact. However, relative slip in the circumferential direction may not occur after the release of tightening torque. The foregoing five types of contact conditions, therefore, must be treated in the numerical approach to accurately analyze the whole tightening process. Shear stresses on each contact surface are assumed to be subject to Coulomb's law of friction.

4.4 Numerical models

The analytical objects are metric coarse screw threads of M 16, and five models with different grip length L_f are prepared, corresponding to the experiments. Figure 6 illustrates an example of finite element mesh pattern for $L_f=60$ mm. Young's modulus and Poisson's ratio of structures composing the bolted joint are supposed to be 200 GPa and 0.3, respectively.

5. Numerical Results

5.1 Effects of friction coefficient

Figure 7 shows the relationship between the rate of change in bolt axial tension γ_1 and the ratio of friction coefficients before the release of tightening

Fig. 6 Finite element mesh (M 16)

Fig. 7 Reduction rates of axial force

torque, μ_{11}/μ_{21} , where the grip length L_f is 35 mm. The reduction in bolt axial tension becomes rather remarkable in the region of μ_{11}/μ_{21} being approximately less than unity. Accordingly, it is recognized that μ_{11} has slightly larger effects on the reduction rate in axial tension than μ_{21} . The differences between experimental and numerical results are rather conspicuous in the region of μ_{11}/μ_{21} being less than unity, which is supposed to be mainly caused by a relatively large amount of scatter in friction coefficients after releasing the tightening torque, thus leading to the scattered relationship between γ_1 and μ_{11}/μ_{21} .

Considering the results shown in Fig. 7 and Fig. 5, which indicates that bolt axial tension F_b starts to decrease when the reduction rate in friction coefficient on nut loaded surface reaches maximum, the characteristics of γ_1 are examined in terms of the friction coefficients concerned. Figure 8 depicts the effects of $\zeta_1 = \mu_{12}/\mu_{11}$ and $\zeta_2 = \mu_{22}/\mu_{21}$, the rates of change in friction coefficients on pressure flank of thread and nut loaded surface, on γ_1 and the rates of change in torque, γ_2 and γ_3 . In each case, the larger the variation rates of friction coefficient, the larger the rates of change in bolt tension and each torque. It can, therefore, be concluded that the numerical method proposed here is effective since fairly close agreements are observed between experimental and numerical results.

5.2 Effects of grip length

The effects of grip length L_f on γ_1 , the rate of

Fig. 8 Reduction rates of axial force and torque

change in bolt axial tension F_b , and γ_2 , the rate of change in thread friction torque T_1 , are indicated in Fig. 9, where L_f is normalized by dividing this by nominal diameter d . From this figure, with decrease of L_f , the amounts of γ_1 and γ_2 slightly decrease. γ_2 varies almost linearly with increase of L_f/d . The amounts of change in γ_1 are small and stay within several percent, and the rates of variation slightly increases with smaller grip length. Although the numerical results for γ_1 by FEM give somewhat higher values than experiment, similar tendencies are observed for varying grip length.

6. Considerations

This chapter presents an insight into the phenomenon that the axial tension of bolt slightly increases just after the release of tightening torque, and then decreases. With increase of the tightening torque applied to nut, the more strain energy is stored in bolt. When the specified tightening torque is attained and the spanner is removed, the twisted bolt would, then, tend to rotate counter-clockwise, in order to release the strain energy accumulated. This counter-clockwise rotation might cause the increase in axial tension as far as the nut would not rotate. Virtually a slight increase is observed while the nut rotation is negligible. However, the sign of nut friction torque T_2 is reversed to balance the thread friction torque T_1 , as the tightening torque T_t is being released. During the process stated above, the amount of friction coefficient on the nut loaded surface becomes small, as shown in Fig. 2, and then the relative sliding would correspondingly occur in the circumferential direction. Consequently, the relative slip might also occur on the thread surface, thereby causing the reduction of bolt axial tension.

It is anticipated that strain energy stored in bolt has a dominant effect on the reductions of axial tension and torque. Therefore, the relationship between the amounts of strain energy stored before and after the release of tightening torque is to be discussed here. A bolt is supposed to be a stepped cylinder, which is subjected to both tension and torque simultaneously, and the cylinder is composed of three parts, such as (a) engaged threads, (b) unengaged threads and (c) cylindrical portion, as illustrated in Fig. 10. L_1 , d and d_2 denote nut thickness, nominal and pitch diameters of screw thread, respectively. The amount of strain energy stored in engaged threads, induced by axial tension and thread friction torque, is calculated in terms of the equation estimating the bolt axial tension at an arbitrary distance from the top face of nut⁽⁴⁾. The relationship between the ratio U_{t2}/U_{t1} and grip length is depicted in Fig. 11, where U_{t1} and U_{t2} repre-

Fig. 9 Reduction rates of axial force and torque

Fig. 10 Elementary model for evaluating strain energy

Fig. 11 Reductions in total strain energy

sent the amounts of total strain energy stored in the bolt before and after the release of tightening torque, respectively. The results obtained by FEM are

Fig. 12 Variations in strain energy

expressed by painted circles. Both results exhibit similar tendencies and give slightly larger variations in the range of small grip length.

Figure 12 shows the reduction rates of strain energy generated by axial tension and thread friction torque, denoted by ΔU_{Fb} and ΔU_{T1} , respectively, both of which are divided by the variation of the total strain energy ΔU_t . Calculations are conducted by the elementary method introduced above. Grip length has minor effects, and about 70% of ΔU_t is the contribution to ΔU_{T1} . Referring to these results, the amount of strain energy to be released is largely affected by the component relevant to torque rather than axial tension. Accordingly, the magnitude of thread friction torque varies more significantly than that of axial tension for varying grip length.

7. Conclusions

In tightening structural members using bolt and nut by torque control method, mechanical behaviors before and after the removal of tightening torque are investigated by experiment and numerical analysis, and the following conclusions are obtained.

(1) Measuring bolt axial tension, torque and coefficients of friction are measured continuously throughout the whole tightening process, the mutual relationship of these factors are elucidated.

(2) When the torque applied to nut is released after the prescribed value is attained, coefficients of friction on pressure flank of screw thread and nut loaded surface immediately begin decreasing, whereas

axial tension of bolt exhibits a slight increase and then decreases. Bolt axial tension starts to decrease when the reduction rate of friction coefficient on nut loaded surface reaches maximum.

(3) A finite element approach is proposed for estimating the variations in torque and axial tension during the tightening process, and its validity is substantiated by comparing the results to those by experiment.

(4) Friction coefficient on nut loaded surface has primary effects on the variations in axial tension and nut friction torque, while the variations in thread friction torque are significantly affected by friction coefficient on pressure flank of screw thread.

(5) The rates of variations in axial tension and thread friction torque, before and after the removal of tightening torque, increase with decrease of grip length.

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