Three-Dimensional Finite Element Analysis during Tightening of Bolt-Nut Connection Having Slight Pitch Difference

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***Abstract*—In a wide industrial field, the bolt-nut joint is unitized as an important machine element although anti-loosening performance is always required. In this paper, the effect of slight pitch difference between bolt and nut is studied. The prevailing torque required for the nut rotation is analyzed before the nut touches the clamped body as well as the tightening torque after the nut touches the clamped body. The results show that a large pitch difference may provide large prevailing torque that causes an anti-loosening effect although a very large pitch difference may deteriorate the bolt tightening force even under a certain tightening torque. By taking into account the anti-loosening and clamping abilities, the most desirable pitch difference is proposed to improve anti-loosening.**

***Index Terms*—bolt-nut connection, tightening torque, tightening force, anti-loosening performance, pitch difference**

I. Introduction

The bolt-nut connections can be regarded as one of the most important mechanical joining techniques. They are widely used in various engineering fields, including aerospace, automotive and mechanical/civil engineering constructions. To ensure the structures safety, high fatigue strength has been required as well as anti-loosening performance. Many previous studies are focusing on the anti-loosening performance for newly developed bolt-nut connections [1, 2, 3] and several studies contribute toward improving fatigue strength [4, 5, 6]. This paper focuses on the effect of pitch difference on the anti-loosing performance. Here, several pitch differences between the bolt and nut are designed as shown in Fig. 1. In the previous studies, although the pitch difference was studied by using axi-symmetric FEM [5], and the effect of pitch difference on the anti-loosening performance has not been clarified yet. Therefore, in this paper, a three-dimensional FEM simulation is applied to calculate the tightening torque as well as the bolt axial force during the tightening process. By taking the anti-loosening performance into account, the most desirable pitch difference will be proposed.

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II. Analysis and Tightening Mechanism

In this study, the Japanese Industrial Standard (JIS) M12 bolt-nut connections with strength grade 8.8 are employed. The bolt material is steel SCM435, and the nut material is medium carbon steel S45C quenched and tempered as shown in Table I. The standard M12 bolt-nut connection has the same pitch $1750\mu m$. But here the nut pitch is assumed to be equal or slightly larger than the bolt pitch as shown in Fig. 2 [7]. Three types of pitch difference $\alpha = 30\mu m$, $\alpha = 40\mu m$ $\alpha = 50\mu m$ are considered in this study. In addition, the horizontal clearance $C_x = 59mm$ is assumed between the bolt-nut threads. When tightening a nut having pitch difference, so called prevailing torque occurs before the nut contact with the clamped body [8, 9] as shown in Fig.2 and Fig.3. Note that tightening torque T is different from prevailing torque T_p .

Fig. 4 shows the three-dimensional mesh used for the finite element analysis. To simplify the calculation, the hexagonal bolt head and nut are replaced by cylinders. The helical thread of the bolt and nut are subdivided into smaller elements compared to the other parts [8, 9]. Contact status and material non-linearity are considered in the analysis. Boundary conditions are provided in the following way. The bottom of the clamped body is fixed as well as the one side of the bolt as shown in Fig. 3. Then, a series of tightening angels are applied on the side surface of the nut. The start position of the analysis is where the prevailing torque appears. And the end position of the analysis is where the nut touches the clamped body.

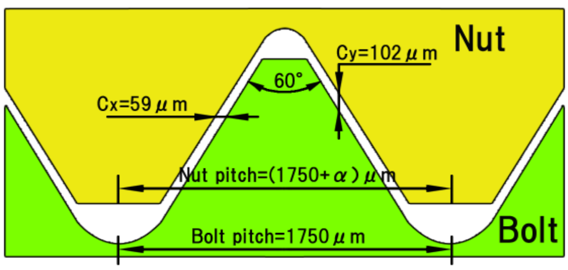

Figure 1. Pitch difference and clearance between bolt and nut.

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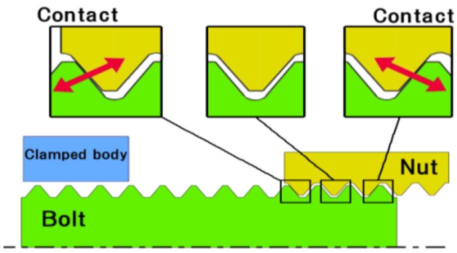

Figure 2. Contact status between bolt and nut, when the nut pitch is slightly larger than the bolt pitch.

TABLE I. MATERIAL PROPERTIES OF BOLT AND NUT.

	Young's modulus (GPa)	Poisson's ratio	Yield strength (MPa)	Tensile strength (MPa)
SCM435 (Bolt)	206	0.3	800	1200
S45C (Nut)	206	0.3	530	980

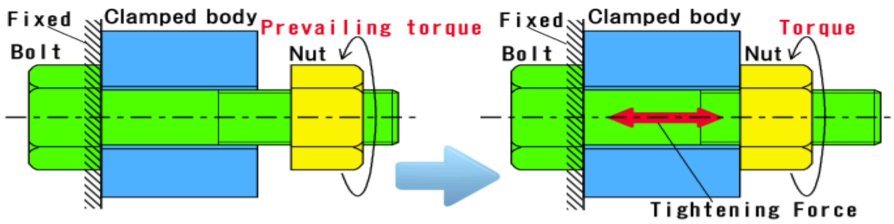

Figure 3. The location where the prevailing torque occurred, and boundary conditions of this simulation.

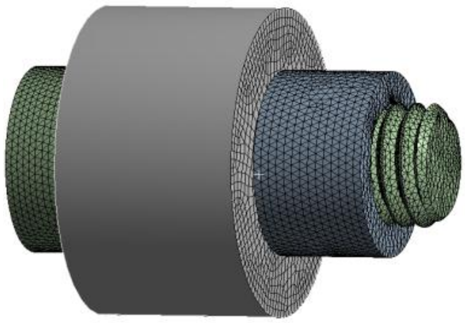

Figure 4. FEM mesh of M12 bolt nut connections.

III. RELATIONSHIP BETWEEN TIGHTENING TORQUE AND NUT ROTAION CYCLE

Fig. 5 schematically illustrates nut screwing process as shown in Position A to Position E. Here, Position A is where the nut begins to contact with the bolt and Position B is where prevailing torque appears. Position C is during the period when prevailing torque is increasing and Position D is where the nut is completely screwed into the bolt and then the prevailing torque is saturated. Position E is where to the nut just touch the clamped body and then the tightening starts. Position E is the end of screwing process and also as the start of the tightening process. Position F is during the tightening process of the clamped body with increasing the tightening force. For both screwing and tightening processes, Figure 6 illustrates the torque and the nut rotation relations for $\alpha = 0\mu m$ and $\alpha = 30\mu m$ obtained by FEM simulation. As shown in the blue line for $\alpha = 0\mu m$, the tightening torque suddenly appears when the nut touching the clamped body without appearing the prevailing torque. As shown in the red line for $\alpha = 30\mu m$, the prevailing torque appears at 4.25 cycles when the nut is screwing into the bolt. Then, the prevailing torque increases and saturated during position D-E as T_p =7 Nm. After the nut touching the clamped body, both of the tightening torque increase up to T =25Nm as shown in Fig. 6.

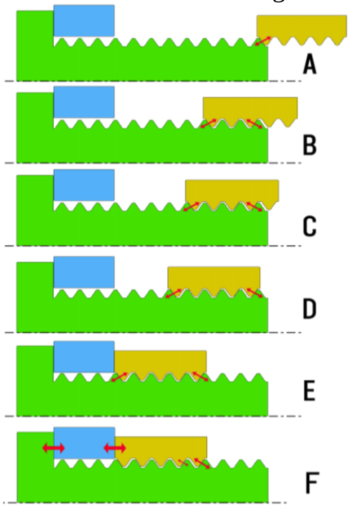

Figure 5. Nut screwing process A-E and tightening process E-F.

IV. RELATIONSHIP BETWEEN TORQUE AND TIGHTENING FORCE

Since the bolt and nut are used for connecting mechanical components and structures, their tightening ability is essential. Therefore, after the nut touches the clamped body, the relationship between the tightening force and the tightening torque should be investigated. To obtain the relationship efficiently, Position E→F in Fig.5, that is, the nut tightening process is focused.

A. *Torque and Tightening Force Relation for Nomal Bolt - Nut*

For normal bolt-nut $\alpha = 0\mu m$, Motosh equation (1) is known where the tightening torque T consists of three parts, that is, the thread surface friction torque $F/2 \cdot d_2/\cos\beta \cdot \mu$, the axial force torque $F/2 \cdot P/\pi$, and the nut seating face friction torque $F/2 \cdot d_w \cdot \mu_w$.

$$T = \frac{F}{2}\left(\frac{d_2}{\cos\beta}\mu + \frac{p}{\pi} + d_w\mu_w\right) \quad d_w = \frac{2(d_o^{\,3} - d_h^{\,3})}{3(d_o^{\,2} - d_h^{\,2})} \qquad \cdots \quad (1)$$

In eqn (1), T is tightening torque, F is tightening force, d_2 is effective diameter, β is half angle of thread (β=30°), d_0 is outside diameter of bolt seat surface, d_h is bolt hole diameter.

B. FEM Tightening Simulation for M16 Bolt-nut

Fig. 7 shows the relationship between the tightening force F and torque and the tightening torque T for M16. The FEM results are compared with the experimental results [5] as well as eqn (1) for $\alpha = 0\mu m$. When $\alpha = 0\mu m$, three results are in good agreement. Overall, the FEM results and experimental results are in good agreement. As shown in Fig.7, it may be concluded that the FEM analysis may predict the tightening process for other bolt diameter without doing experiment.

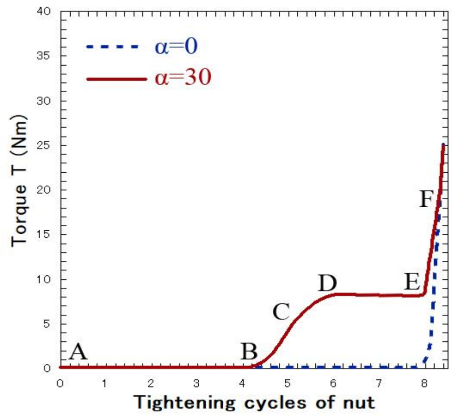

Figure 6. Torque- nut tightening cycle relation by FEM.

C. FEM Tightening Simulation for M12 Bolt-nut

Fig. 8 shows the relationship between the tightening torque and the tightening force obtained by FEM analysis for M12. When the pitch difference $\alpha = 30\mu m$, the small prevailing torque may cause the nut loosening. When the pitch difference $\alpha = 50\mu m$, the prevailing torque is large but the bolt axial force is too small. The pitch difference $\alpha = 40\mu m$ may be the most suitable because of the prevailing torque is large enough without losing the tightening ability.

D. Relationship between Prevailing Torque and Pitch Difference

As shown in Fig.7 and Fig.8, for the normal nut $\alpha = 0\mu m$, the tightening force increases from T =0. However, for the pitch difference nut, the initial tightening torques $T \neq 0$ to produce initial tightening force F. This is because to screw the nut having the pitch difference, a prevailing torque $T_p > 0$ is necessary even before the nut contacts with the clamped body. Therefore, during the tightening process of the pitch difference nut, some portion of the torque T should be used as a kind of the prevailing torque and only the remaining portion can be used for tightening. In other words, the subtracted torque $T - T_p$ is converted into the tightening force.

E. Slope of $F - T$ relation vs. Pitch Difference

As shown in Fig. 7 and Fig. 8, the slope of $F - T$ relation for the pitch difference nut is larger than the slope of $F - T$ relation for the normal nut. This is because with increasing the nut torque during tightening process, the internal bolt axial force F_α caused by the pitch difference is gradually transformed into the tightening force F as shows in Fig. 10. As shown in Fig.8, at Point F, the $F - T$ relation of $\alpha = 30\mu m$ coincides with the $F - T$ relation of $\alpha = 0\mu m$. Figure 10 illustrates how the contact status change at Point F for bolt-nut having pitch difference in comparison with Fig.9 for normal bolt-nut. As shown in Fig. 9 (b), (c), before and after Point F, the contact status is the same for the normal nut. However, as shown in Fig. 10 (b), (c), the contact status is changed as shown for the pitch difference nut.

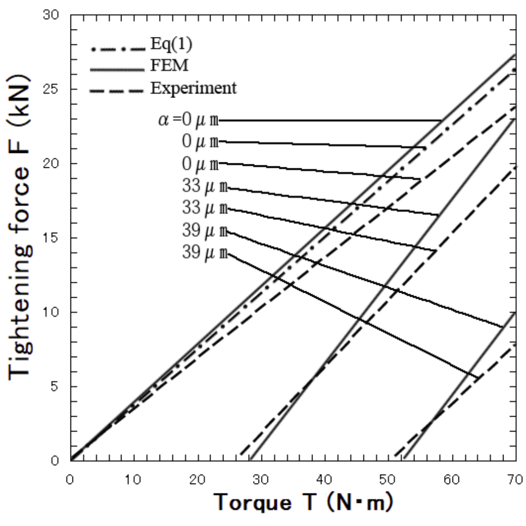

Figure 7. Relationship between tightening force and torque of M16.

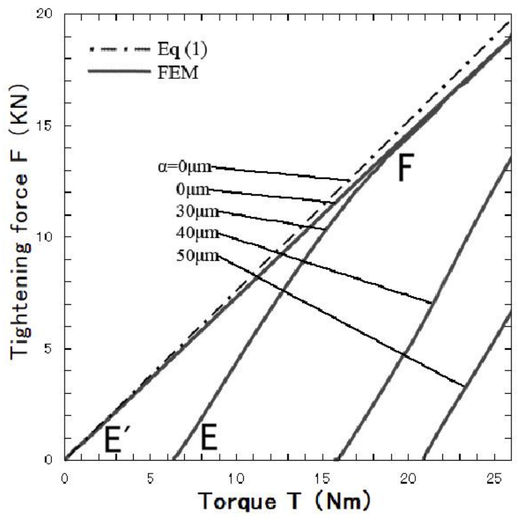

Figure 8. Relationship between tightening force and torque of M12.

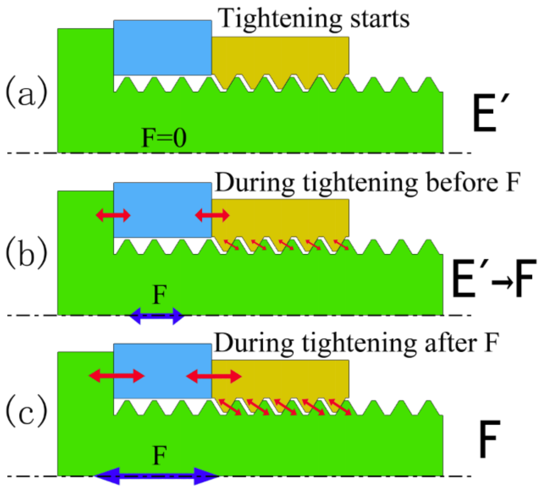

Figure 9. Contact status between normal bolt-nut threads during tightening in Fig. 8.

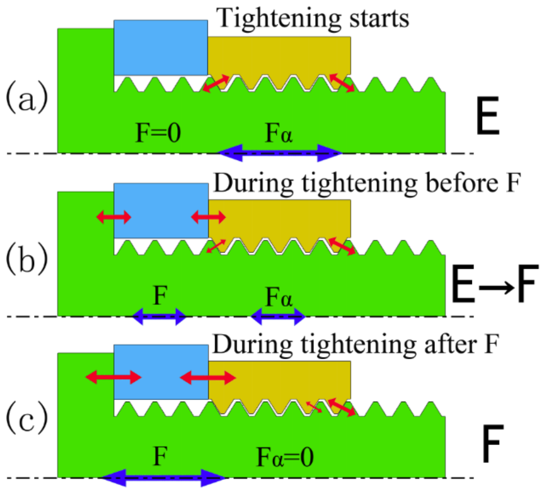

Figure 10. Contact status between bolt-nut threads having pitch difference during tightening in Fig. 8.

V. Conclusion

In this paper, the three-dimensional FEM simulation was performed for tightening the nut having pitch difference. The conclusions can be summarized in the following way.

(1) The prevailing torque can be obtained for several pitch difference by the FEM simulation since the results coincide with the experimental results.

(2) The relationship between tightening force and tightening torque also can be predicted by FEM simulation since the results coincide with the experimental results.

(3) Suitable pitch difference can be discussed to obtain the appropriate prevailing torque and appropiate tightening force.

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