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3D finite element analysis of tightening process of bolt and nut connections with pitch difference

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Abstract. In a wide industrial field, the bolt-nut joint is unitized as an important machine element and anti-loosening performance is always required. In this paper, the effect of a slight pitch difference between a bolt and nut is studied. Firstly, by varying the pitch difference, the prevailing torque required for the nut rotation, before the nut touches the clamped body, is measured experimentally. Secondly, the tightening torque is determined as a function of the axial force of the bolt after the nut touches the clamped body. The results show that a large value of pitch difference may provide large prevailing torque that causes an anti-loosening effect although a very large pitch difference may deteriorate the bolt axial force under a certain tightening torque. Thirdly, a suitable pitch difference is determined taking into account the anti-loosening and clamping abilities. Furthermore, the chamfered corners at nut ends are considered, and it is found that the 3D finite element analysis with considering the chamfered nut threads has a good agreement with the experimental observation. Finally, the most desirable pitch difference required for improving anti-loosening is proposed.

1. Introduction

The bolt-nut connections can be regarded as one of the most important material 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 [1-3], and many studies contribute toward improving fatigue strength [4-6]. This paper, therefore, focuses on the effect of pitch difference in a connection on the anti-loosing performance. Here, several pitch differences between the bolt and nut are designed as shown in figures 1 and 2, the nut pitch is larger than the bolt pitch. However, the previous studies on pitch difference were limited to fatigue strength improvement, and the effect of pitch difference on the anti-loosening performance has not been investigated yet. There is no three-dimensional model is available. This paper, a three-dimensional FEM simulation is used to calculate the tightening torque and the tightening force during the tightening and loosening process. Taking the anti-loosening performance into account, the most desirable pitch difference will be proposed.

2. Experimental and analytical method of tightening and loosening mechanism

2.1. Specimen and experiment equipment
In this study, the Japanese Industrial Standard (JIS) M12 bolt-nut connections with strength grade 8.8

are employed as shown in figure 2. The bolt material is chromiummolybdenum steel SCM435, and the nut material is medium carbon steel S45C quenched and tempered. The standard M16 bolt-nut connection has the same pitch dimension of 1750 μm, here, the nut pitch is assumed to be equal or slightly larger than the bolt pitch (figure 3) [7]. Three types of pitch differences, namely α=30 μm, α=40 μm and α=50 μm, are considered in this study. In addition, the horizontal clearance of a bolt and a nut (Cx) is 59 mm. when tightening a nut with pitch difference, torque occurs before the nut contact with the clamped body, and the torque occurred in this period is called prevailing torque [8,9] as shown in figure 4.
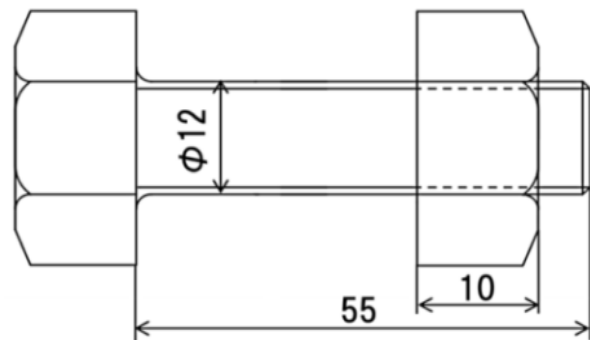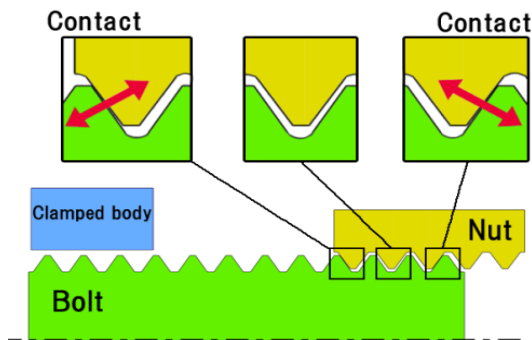

Figure 1. Contact status between bolt and nut, when the nut pitch is slightly larger than the bolt pitch.

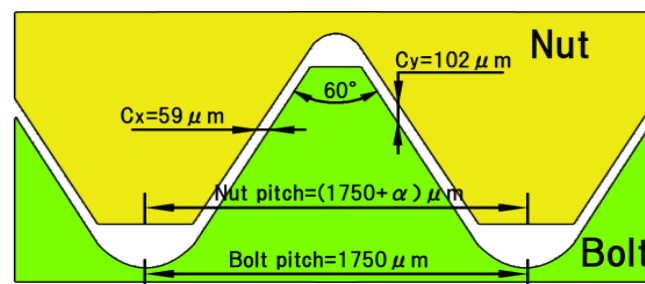**Figure 2.** M12 Bolt-nut specimen (dimensions in mm).

Figure 3. Pitch difference and clearance between bolt and nut.
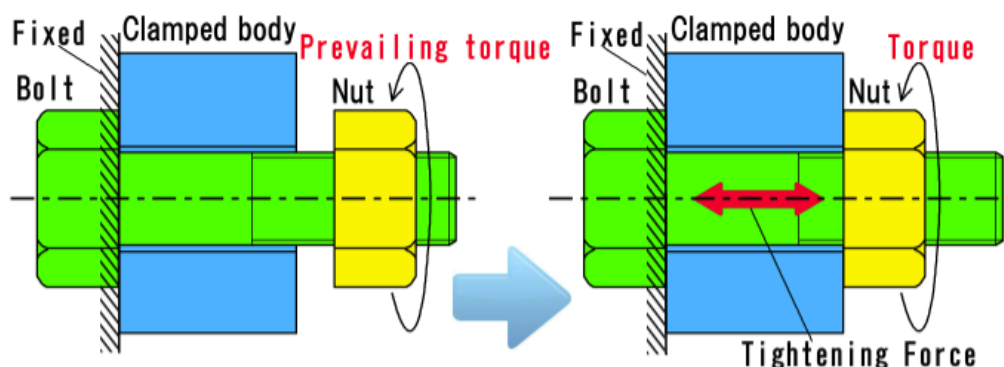

Figure 4. FEM model and boundary conditions for prevailing torque analysis.

2.2. Experimental conditions

The method to measure prevailing torque is shown in figure 5. The model of the torque wrench is TOHNICHI DB 50 N, and lubricating oil is MoS_2. Start from the position where the blot and nut begin

to connect (0 turns), record the prevailing torque every 45° the nut is tightened. After the whole nut (5.7 turns) are tightened in the bolt, continue tighten the nut 2.3 turns, thus the nut is tightened in the bolt 8 turns in total. Then, loosen the nut until the bolt and the nut separate from each other, and record the prevailing torque every 45° the nut is tightened.
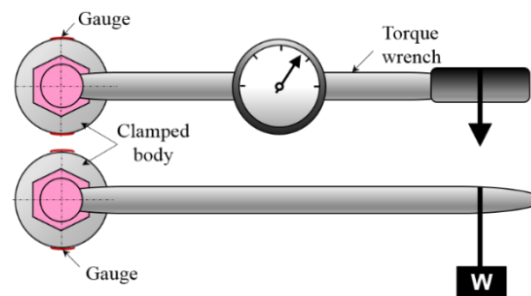

Figure 5. Torque measuring device.

2.3. Analytical method

A precise three-dimensional model as shown in figure 6 is used for finite element analysis. To simplify the calculation, the hexagonal part of the bolt and the nut is replaced by two cylinders. Especially, the helical thread of the bolt and nut were subdivided into smaller elements compared with other parts [10]. Contact types and material non-linearity are considered in the analysis. Boundary conditions are set as follows, one side of the bolt is fixed, a set of tightening angels are applied on the side surface of the nut, and then loosen the nut. The connecting way of the nut and the bolt is frictional contact. The start position of the analysis is where the prevailing torque begins to occur and the end position of the analysis is where 2.3 cycles tightened after all the nut thread is tightened into bolt.
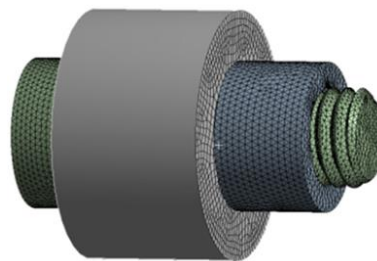

Figure 6. FEM model of M12 bolt and nut.

Table 1. Material properties of bolt and nut.

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

3. Comparison of experimental result and analytical result of prevailing torque

3.1. Tightening process

Figure 7(d) is a schematic diagram of nut tightening process. From A to E is the process of tightening, and from E to A is the process of loosening. In figure 7(d), A is the position where the nut begins to contact with the bolt, B is the position where prevailing torque begins to occur, C is in the period when prevailing torque is increasing, D is the position where the nut is completely tightened into the bolt, E

is the position where to continue to tighten the nut for 2.3 turns until the nut contact with clamped body. Figures 7(a) to 7(c) shows the prevailing torque in the tightening and loosening process obtained by experiment and FEM simulation. The red line from A to E shows the process of the tightening, and the blue line from E to A shows the process of loosening. The FEM results of the solid line are in good agreement with the dotted line of the experimental results. It is found that prevailing torque remains steady after the nut was completely screwed into the bolt (from position D to position E), and the positions from D to E are called convergent position. And the average of those data of the convergent positions was calculated to represent the convergent positions.

3.2. Comparison of experimental result and analytical result of prevailing torque
Figure 7(a) shows the measured results when α=30 μm, and it can be seen that prevailing torque begins to occur when the nut is tightened into the bolt for 4.2 turns, the average of the convergent prevailing torque is 4.7 Nm. And analytical result can be seen that prevailing torque begins to occur when the nut is tightened into the bolt for 4.25 turns, the average of the convergent prevailing torque is 7 Nm.

(a) α=30 μm

(b) α=40 μm

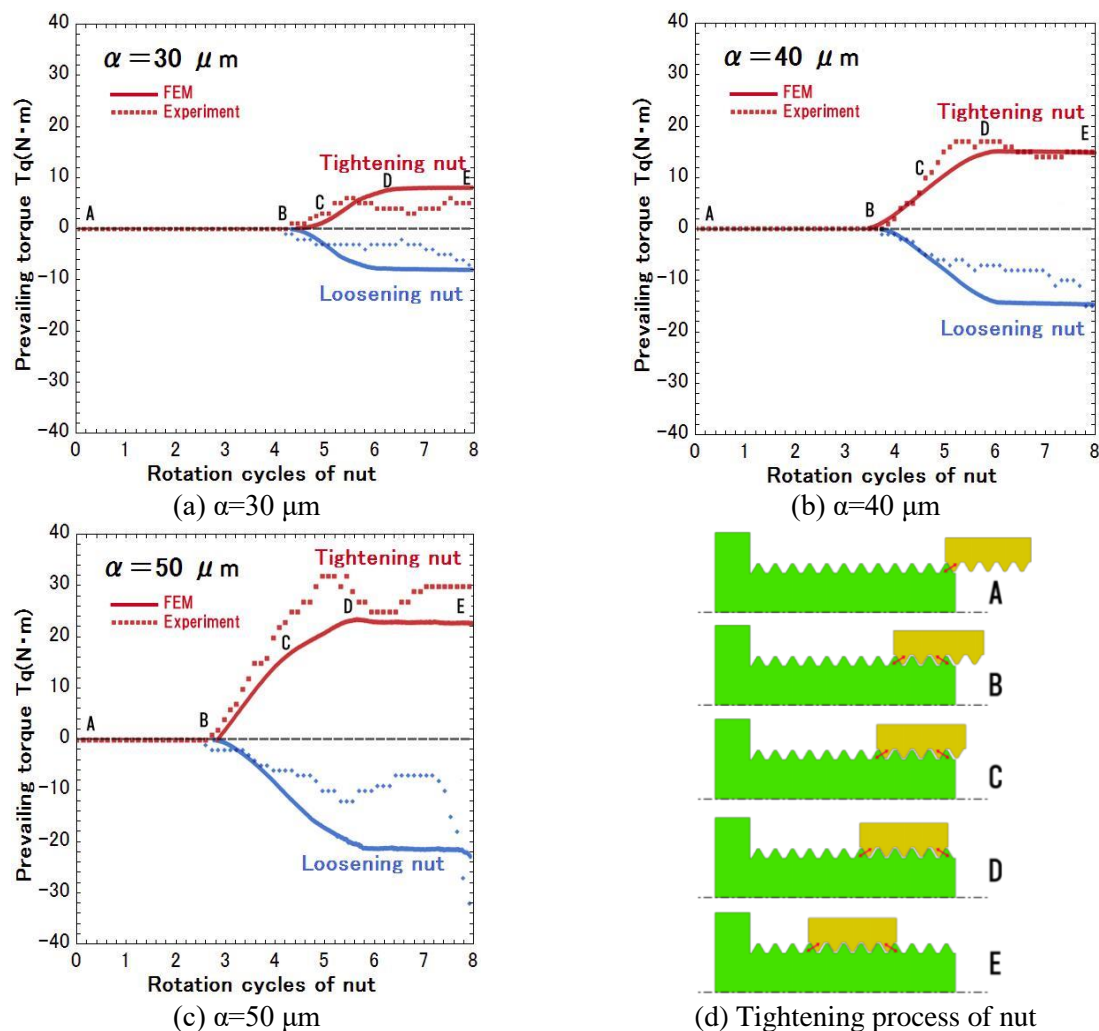(c) α=50 μm

(d) Tightening process of nut

Figure 7. Results of prevailing torque simulation by 3D FEM in comparison with experimental measurement.

Figure 7(b) shows the measured results when α=40 μm, and it can be seen that prevailing torque begins to occur when the nut is tightened into the bolt for 3.9 turns, the average of the convergent prevailing torque is 14.6 Nm. And analytical result can be seen that prevailing torque begins to occur when the nut is tightened into the bolt for 2.8 turns, the average of the convergent prevailing torque is 16 Nm.

Figure 7(c) shows the measured results when α=50 μm, and it can be seen that prevailing torque begins to occur when the nut is tightened into the bolt for 2.6 turns, the average of the convergent prevailing torque is 29.9 Nm. And analytical result can be seen that prevailing torque begins to occur when the nut is tightened into the bolt for 2.8 turns, the average of the convergent prevailing torque is 23 Nm.

4. FEM analysis of tightening process of the nut

4.1. Analytical method
Figure 5 shows the FEM model, a clamped body was added in the connection compared with the model in previous sections. The boundary conditions are shown in figure 6. The head of the bolt and the bottom of the clamped body were fixed. The simulation begins at position B at which the nut began to be tightened, and the nut finally reaches position E at where the nut begins to contact with the clamped body after it passes through position C and position D. Then, continues to tighten a certain angle, during which period a tightening force to compress the clamped body will be generated. The contact type of the thread surface of the bolt and the nut was set as frictional contact, and so were the bottom surface of the nut and the top surface of the clamped body. Here, our special interest focus on the relationship between the tightening torque and tightening force from position E to position F (figure 8).
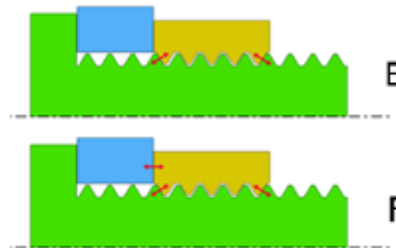

Figure 8. Tightening process of nut.

4.2. Comparison of torque formula and analysis in normal bolt · nut (α = 0)
When tighten the common nut into the bolt, the generated tightening torque consists of three parts, the screw surface friction torque $F/2 \cdot d_2/\cos\beta \cdot \mu$, the axial force torque $F/2 \cdot P/\pi$, and the seating surface friction torque $F/2 \cdot d_w \cdot \mu_w$, and it is shown in the following equation called Motosh equation.

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

Here, tightening torque T, tightening force F, effective diameter $d2$, half angle of thread β, outside diameter of bolt seat surface $d0$, bolt hole diameter dh. The relationship between the tightening torque and the tightening force of M12 obtained by this evaluation formula and analysis shows in figure 8. The evaluation formula and the analysis result agreed well within an error of 5%. From this result, it is considered that the analysis result of α=0 is high in accuracy.

4.3. 3-D analysis during the tightening process of pitch difference nut
Since the bolt and nut are used for connecting components or structures, the tightening ability to

produce enough tightening force is essential. Therefore, after the nut touches the clamped body, the relationship between the tightening torque and the tightening force was investigated. Note that tightening torque T is different from prevailing torque Tp, which is defined only before the nut touches the clamped body. To obtain the relationship between torque and tightening force, Three-dimensional finite element analysis is applied.

Figure 9 shows the relationship between the tightening torque and the tightening force obtained by FEM analysis of M12 bolt and nut with pitch difference. Although the tightening force of pitch difference α=30 is large, insufficient prevailing torque can cause the nut to loosen. The prevailing torque of pitch difference α=50 is large, but a sufficient tightening force cannot be imparted. The pitch difference α=40 is considered to be the most suitable for anti-loosening performance because the prevailing torque and tightening force are both sufficient.
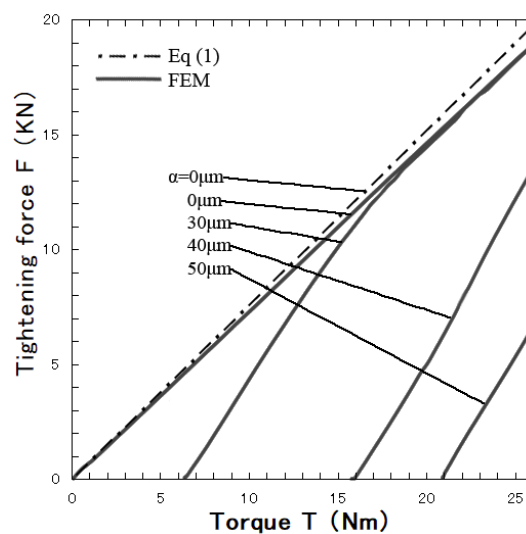

Figure 9. Relationship between torque and tightening force.

When a common nut is tightened, the tightening forces increase from 0. However, if there is a pitch difference between the nut and bolt, the initial points of tightening forces will no longer be 0. The reason for this is that when tighten pitch a difference nut, there will be prevailing torque between the bolt-nut connections before the nut contacts with the clamped body. Thus, when tighten a pitch difference nut with a certain torque T, a part of the torque needs to be used to offset the prevailing torque, and the other part of the torque, which equals to T-Tp, will convert into tightening force. Therefore, when the tightening torque is fixed, the tightening force decreases with the increase of pitch difference, meanwhile, the prevailing torque increases with the increase of pitch difference.

5. Conclusion
In this paper, the following results were obtained by tightening and loosening experiments on bolts and nuts with different pitch differences and analysis by three-dimensional finite element method.
- When pitch difference is 30 μm, the corresponding prevailing torque equals to 4.7 Nm; when pitch difference is 40 μm, the corresponding prevailing torque equals to 14.6 Nm; when pitch difference is 50 μm, the corresponding prevailing torque equals to 29.9 Nm, in the experiment.
- Suitable pitch difference can maintain the good anti-loosening performance in the whole loosening process, and this has been proved by FEM simulation.
- The relationship between tightening force and tightening torque can be predicted by FEM simulation. In order to obtain the appropriate tightening force and tightening torque, the optimum pitch difference should be 40 μm.

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