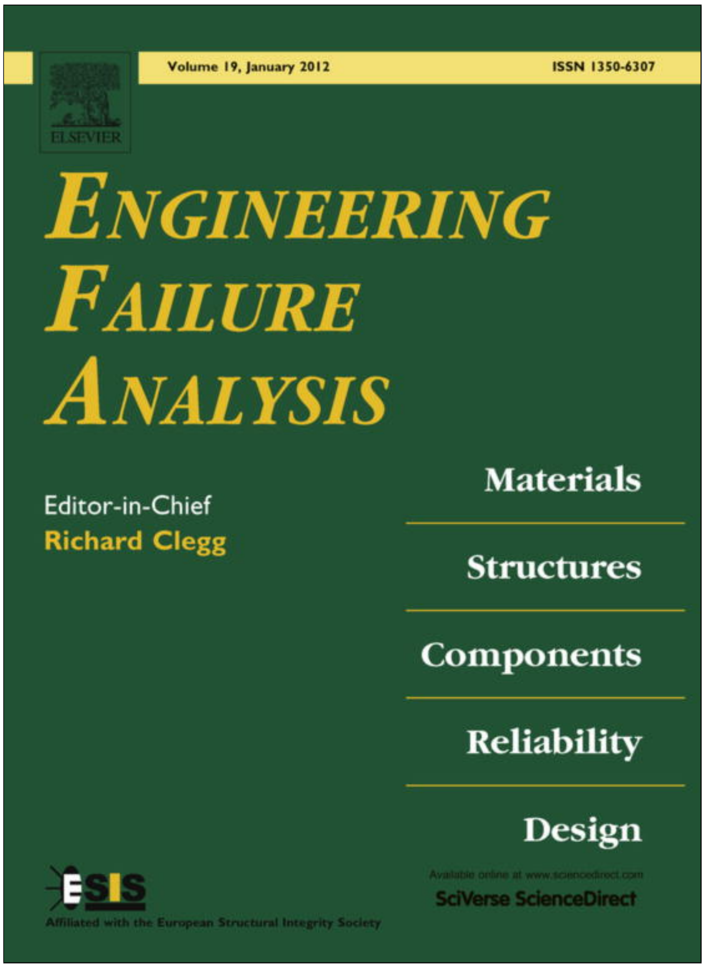

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Investigation into the self-loosening behavior of bolted joint subjected to rotational loading

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A B S T R A C T

The self-loosening mechanisms of a bolted joint subjected to a rotational load were investigated using three-dimensional FEM. A previous theory regarding the conditions of initiation and progress of loosening was verified. Loosening occurs if the relative rotation angle applied to the bolt reaches a critical value θ_{cr} and the thread surface undergoes a complete slip. In addition, loosening progresses if $T_{sl} < T_w < T_{st}$ holds, where T_{sl}, T_{st}, and T_w are the loosening and the tightening torque of the thread surface, and the slip torque of the bearing surface, respectively. If above conditions hold, bolt tension decreases in proportion to the relative rotation angle of the bolt during complete thread-surface slip while bolt tension does not change during complete bearing-surface slip. If these conditions do not hold, loosening does not progress even if the thread or the bearing surface undergoes complete slip. In order to verify the above loosening mechanism, a loosening test was carried out. It was confirmed that the loosening progressed by the same mechanism as that shown by FEM.

1. Introduction

Bolted joints are widely used to assemble mechanical products and structures due to their ease of disassembly for maintenance and their relatively low cost. However, fatal accidents due to joint failure are still frequent. It is supposed that one of the primary failure modes of bolted joints is loosening.

It is known that the load applied in the transverse and rotational directions is the primary loading mode that causes self-loosening. As to the loosening due to rotational load, Sakai [1] and Fujioka and Sakai [2] investigated the loosening mechanism and proposed the conditions by which loosening is initiated and progresses, specifically the torque required to cause slip on the thread and the bearing surfaces. On the other hand, as to the loosening due to a transverse load, the authors [3] performed three-dimensional FEM analysis and explained the joint behavior in relation to the contact state on the thread and the bearing surfaces. Then, Fujioka [4] investigated the loosening mechanism of a bolted joint subjected to simultaneous loading in the rotational and transverse directions using FEM.

In the present study, the self-loosening mechanism of a bolted joint subjected to rotational loading is investigated using FEM and explained in relation to the contact state on the thread and the bearing surfaces. The result is verified by the theory of the initiation and the progress of loosening proposed by Sakai [1] and an experimental result. In Section 2, Sakai's theory [1] is summarized. Next, in Section 3, the FEM model is shown. Then, in Section 4, the loosening mechanism is explained on the basis of FEM results. Finally, in Section 5, an experimental result is shown to verify the loosening mechanism.

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2. Existing theory

The theory proposed by Sakai [1] that describes the mechanism of self-loosening due to rotational loading is introduced here referring to the setting shown in Fig. 1. The upper and lower jigs are tightened by a bolt and nut pair to develop bolt tension F_b and a torque T is applied to the jigs in the hydraulic testing machine. In this setting, the torques that are required to cause the loosening and tightening slip on the thread surface and the slip on the bearing surface are expressed as T_{sl}, T_{st}, and T_w, respectively;

$$T_{sl} \approx \frac{F_b}{2}\left(\frac{d_2}{\cos\alpha_1}\mu_s - \frac{P}{\pi}\right), \tag{1}$$

$$T_{st} \approx \frac{F_b}{2}\left(\frac{d_2}{\cos\alpha_1}\mu_s + \frac{P}{\pi}\right), \tag{2}$$

$$T_w = \frac{F_b}{2} d_w \mu_w, \tag{3}$$

where μ_s, μ_w, d_2, d_w, P, and α_1 are the coefficients of friction on the thread and the bearing surfaces, pitch diameter of the thread, equivalent diameter of the bearing surface, thread pitch, and thread half angle, respectively. In order for the bolt to keep rotating in the loosening direction, it is necessary that the thread surface undergoes a complete slip while torque is applied in the loosening direction and the bearing surface undergoes a complete slip while torque is applied in the tightening direction. That is, the condition below needs to hold;

$$T_{sl} < T_w < T_{st}. \tag{4}$$

The rotation angle on the thread surface during loading in the loosening direction corresponds to the loosening rotation angle.

The relative rotation angle θ_{cr} needs to be applied to the jigs in order for the bolt to initiate rotation in the loosening direction in addition to the conditions expressed in Eq. (4). Loosening rotation does not occur if the relative rotation angle of the jigs is less than θ_{cr} because it causes only the torsion of the bolt axis and does not cause a complete slip on the thread surface. θ_{cr} can be expressed as the sum of the tightening torque left in the bolt axis T_w and the loosening torque on the thread surface T_{sl},

$$\theta_{cr} = \frac{(T_{sl} + T_w)l}{I_p G} = \frac{F_b l}{2 I_p G}\left(\frac{d_2}{\cos\alpha_1}\mu_s - \frac{P}{\pi} + d_w \mu_w\right). \tag{5}$$

where l and I_p are the grip length and the polar moment of inertia of the bolt axis, respectively.

3. Finite element analysis model

The FEM model that corresponds to the bolted joint shown in Fig. 1 is shown in Fig. 2. A general-purpose FEM software, ANSYS 11.0, was used. The nominal diameter of the bolt and nut pair was M16 and the grip length was 30 mm. The bolt and nut each have two pitches of thread and only one pitch is engaged in the FE model in order to simplify the mechanical behavior on the thread surface expressed by contact force and slip displacement distributions. This simplification has some effect since the stiffness of the engaged thread becomes low compared to that of the actual bolted joints. However, the essential behavior of bolted joint has been reproduced using the models with one to two pitches of thread because the self-loosening behavior is mainly caused by the slip on the contact surfaces [4,5]. The outer shape of the bolt head and the nut was modeled

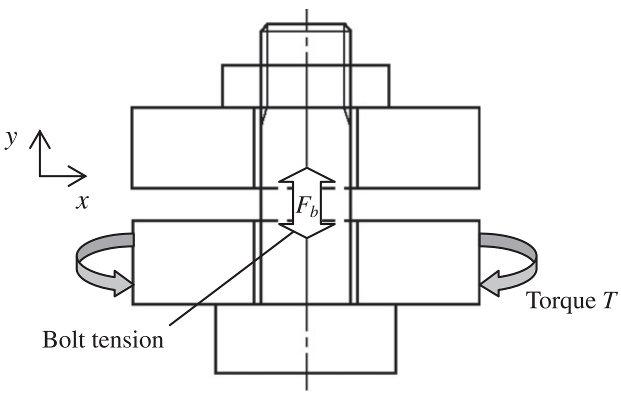

Fig. 1. Bolted joint model.

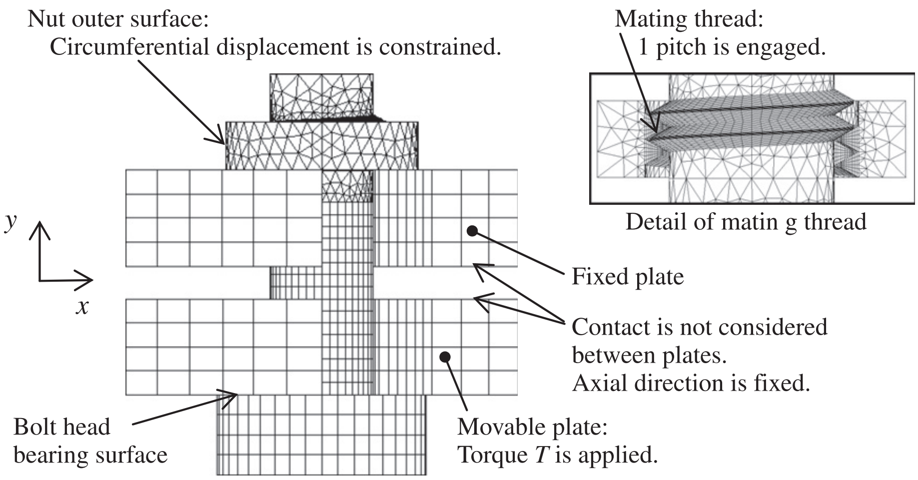

Fig. 2. FE model.

as a cylinder whose outer diameter is the width across the flat of the actual hexagonal shape. As to the jigs, only the bearing surface part was modeled as a plate. The plate under the bolt head was movable while that under the nut was fixed.

Contact elements were used to incorporate contact behavior at all the interfaces such as the engaged thread surface, bolt head bearing surface, and nut bearing surface. However, it was assumed that the rotation of the nut is not allowed because both bolt and nut prevent rotating. Therefore, the contact surfaces that affected the loosening behavior were the thread and the bolt head bearing surfaces. The pure penalty method was employed as a contact algorithm and the Coulomb friction law was considered. The coefficient of friction on the thread surface μ_s was set as 0.10. In order to investigate the behavior in both cases in which Eq. (4) holds and does not hold for $\mu_s = 0.10$, the coefficient of friction on the bearing surface μ_w was set as 0.04, 0.10, and 0.12. As to the boundary conditions, the fixed plate was constrained in the axial direction while the movable one was displaced in that direction to develop a bolt tension. In addition, the edge lines of the fixed plate were constrained in the transverse directions while the edge curve of the movable plate was constrained in the radial direction and displaced or loaded in the circumferential direction to apply a torque. The outer surface of the nut was constrained in the circumferential direction to prevent rotation. The Young's modulus and Poisson's ratio for all components (bolt, nut, and two plates) were 205 GPa and 0.3, respectively. The FEM analysis performed was quasi-static and elastic. Geometric nonlinearities were taken into account.

4. Finite element analysis results

4.1. Mechanism of self-loosening

The results of FEM analysis performed under the conditions of $\mu_s = 0.10$, $\mu_w = 0.10$, and applied angle 0.156° are shown. Under these conditions, $T_{sl} < T_w < T_{st}$ holds. Firstly, the torque–rotation angle relation of the movable plate is shown in Fig. 3. This figure includes the results that correspond to the three values of μ_w. Here, positive torque corresponds to loosening torque. You can see that the relation has a hysteresis loop involving a sloped and a flat region. For the case of $\mu_w = 0.10$, the maximum torque in the loosening direction (upper flat region) corresponds to the loosening torque on the thread surface

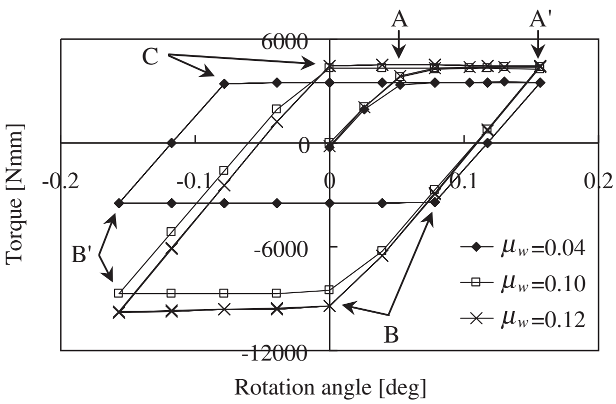

Fig. 3. Torque–angle relation.

T_{sl}. The FEM result was 4.36×10^3 N mm and agrees well with the calculation using Eq. (1), which results in $T_{sl} = 4.35 \times 10^3$ N mm. On the other hand, the maximum torque in the tightening direction (lower flat region) corresponds to the torque that causes complete slip on the bearing surface T_w. The FEM result is 8.71×10^3 N mm and agrees with the calculation using Eq. (3), which results in $T_{sl} = 8.80 \times 10^3$ N mm. The slope of the sloped region is 9.10×10^4 N mm/deg and smaller than the torsion stiffness of the bolt of 1.19×10^5 N mm/deg. That is because the rotation angle of the movable plate comprises not only the bolt torsion but also the micro slip on the thread and the bearing surfaces. Secondly, variation in the rotation angle of the bolt is shown in Fig. 4a. Symbols such as A and B in the figure correspond to the slope change points in Fig. 3. The variation in the rotation angle can be explained in relation to the torque–angle relation shown in Fig. 3 and the contact state on the thread and bearing surfaces shown in Fig. 5. Firstly, in the sloped region in the loosening process (OA and B'C), the bearing surface is in a state of complete stick while the stick region shrinks gradually on the thread surface as shown in Fig. 5a. Therefore, the bolt head rotates with sticking to the movable plate and the bolt thread rotates slightly in the

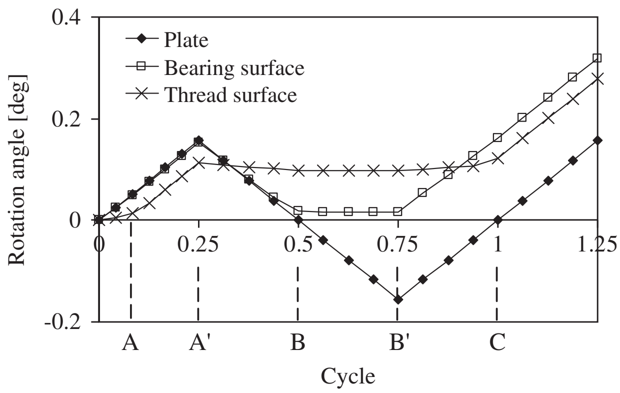

Fig. 4a. Rotation angle for the case $\mu_s = 0.10$ and $\mu_w = 0.10$.

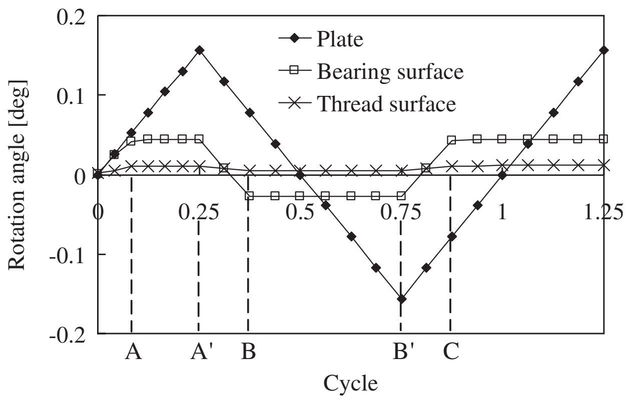

Fig. 4b. Rotation angle for the case $\mu_s = 0.10$ and $\mu_w = 0.04$.

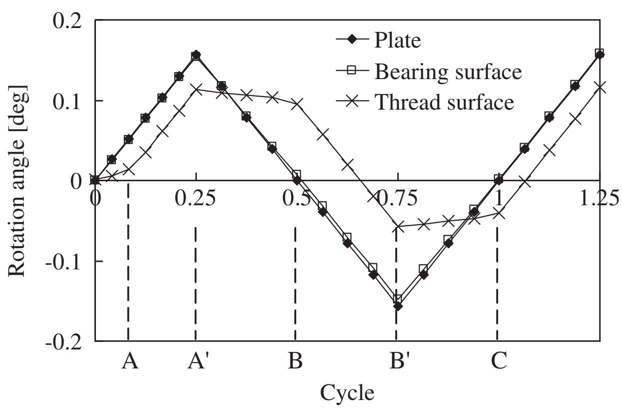

Fig. 4c. Rotation angle for the case $\mu_s = 0.10$ and $\mu_w = 0.12$.

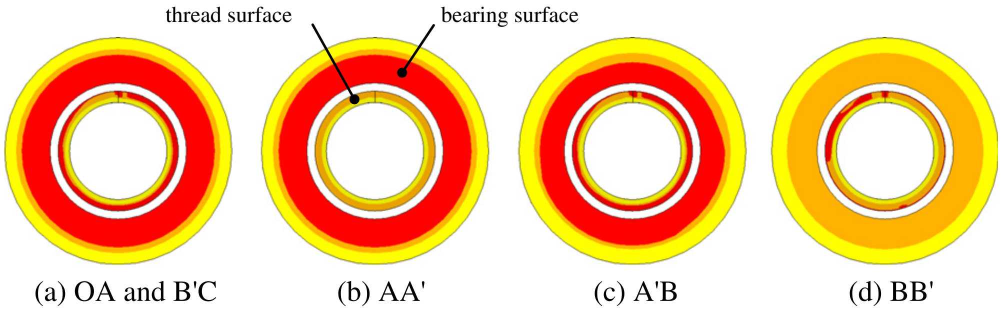

Fig. 5. Evolution of contact states for the case of $\mu_s = 0.10$ and $\mu_w = 0.10$.

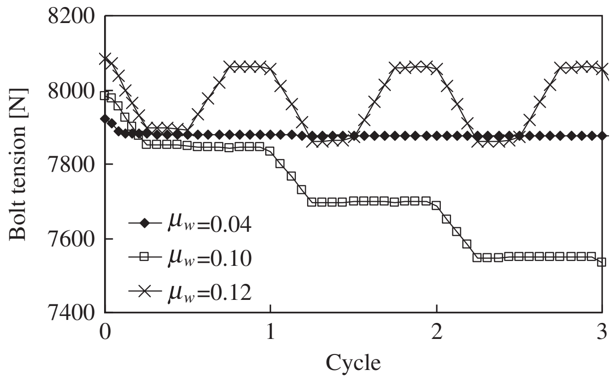

Fig. 6. Variation in bolt tension.

loosening direction. The difference in the rotation angle between the thread and the bearing surfaces indicates the torsion of the bolt axis. Next, in the flat region (AA'), the thread surface undergoes complete slip as shown in Fig. 5b. Therefore, the bolt rotates while sticking to the movable plate and maintaining the bolt torsion. When the torque turns to the tightening direction, a stick region reappears on both the thread and bearing surfaces as shown in Fig. 5c in the sloped region (A'B). Thus, the bolt head rotates with sticking to the movable plate and the bolt thread rotates slightly in the tightening direction. In this process, the direction of the bolt torsion changes from the loosening direction to the tightening direction. Finally, in the flat region (BB'), the bearing surface undergoes complete slip as shown in Fig. 5d. Therefore, only the movable plate rotates while the bolt does not rotate. In the initial loosening process (OA), the bolt torsion angle becomes constant after the thread surface undergoes a complete slip. This torsion angle corresponds to θ_{cr}. However, it corresponds to the case of $T_w = 0$ in Eq. (5) because tightening torque is not applied when the bolt tension develops. Lastly, the decrease in bolt tension is shown in Fig. 6. It can be seen that bolt tension decreases drastically in the flat region of the torque–rotation angle relation in the loosening process. The decrease is in proportion to the rotation angle of the movable plate during the process represented by the flat region of the diagram.

4.2. Effect of the difference between the coefficient of friction on the thread surface and that on the bearing surface

Firstly, the results of FEM analysis performed in the condition of $\mu_s = 0.10$, $\mu_w = 0.04$, and applied angle 0.156° are shown. Under these conditions, $T_w < T_{sl} < T_{st}$ holds. In the torque–rotation angle relation of the movable plate for the case of $\mu_w = 0.04$ shown in Fig. 3, the maximum torque both in the loosening direction (upper flat region) and in the tightening direction (lower flat region) corresponds to the slip torque of the bearing surface T_w. The FEM result almost agrees with the calculation using Eq. (3). The slope of the sloped region is the same as in the case of $\mu_w = 0.10$. Secondly, variation in the rotation angle of the bolt is shown in Fig. 4b. Both the thread and the bearing surfaces undergo sticking in the sloped region in both the loosening and tightening processes (OA, A'B, and B'C). Therefore, the bolt head rotates with sticking to the movable plate and the thread surface rotates slightly in the direction in which torque is applied. This leads to the torsion of the bolt axis. Next, in the flat region (AA' and BB'), the bearing surface undergoes a complete slip. Therefore, only the movable plate rotates while the bolt does not rotate. Lastly, as to the variation in bolt tension shown in Fig. 6, it can be said that self-loosening does not progress in this case because only slight rotation repeats in the loosening and tightening directions on the thread surface and the variation in the bolt tension is negligible.

Next, the results of FEM analysis performed in the conditions of $\mu_s = 0.10$, $\mu_w = 0.12$, and applied angle 0.156° are shown. Under these conditions, $T_{sl} < T_{st} < T_w$ holds. Firstly, in the torque–rotation angle relation of the movable plate shown in Fig. 3, the maximum torque in the loosening direction (upper flat region) corresponds to the loosening torque of the thread surface T_{sl} while the maximum torque in the tightening direction (lower flat region) corresponds to the tightening torque of the thread surface T_{st}. Both torque values agree well with the calculation using Eqs. (1) and (2), respectively. The slope of the sloped region is the same as in the case of $\mu_w = 0.10$. Secondly, variation in the rotation angle of the bolt is shown in Fig. 4c. The bearing surface is in a state of complete stick while the stick region on the thread surface shrinks gradually in the sloped region in both the loosening and tightening processes (OA, A'B, and B'C). Therefore, the bolt head rotates with sticking to the movable plate and the thread surface rotates slightly in the direction where torque is applied. This leads to the torsion of the bolt axis. Next, in the flat region (AA' and BB'), the thread surface undergoes a complete slip. Therefore, the bolt rotates while sticking to the movable plate and maintaining the bolt torsion. Lastly, as to the variation in bolt tension shown in Fig. 6, it is large in the case of $\mu_w = 0.12$ because large rotation occurs in both the loosening and tightening directions on the thread surface. However, self-loosening does not progress because the difference in the rotation angle in the two directions is negligible.

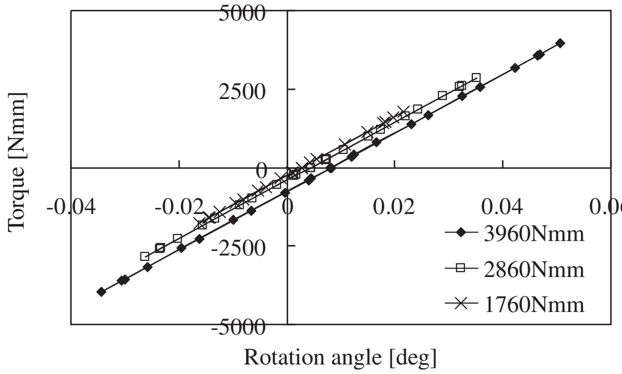

Fig. 7. Torque–angle relation during 20th cycle for the case applied torque is set smaller than T_{sl} for $\mu_s = 0.10$ (4350 N).

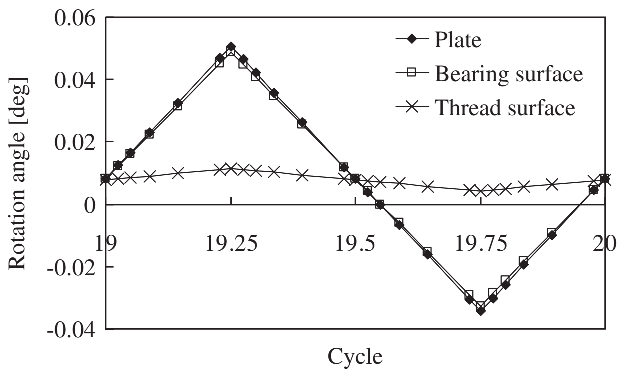

Fig. 8. Rotation angle during 20th cycle for the case of $\mu_s = 0.10$, $\mu_w = 0.10$, and $T = 3960$ N mm.

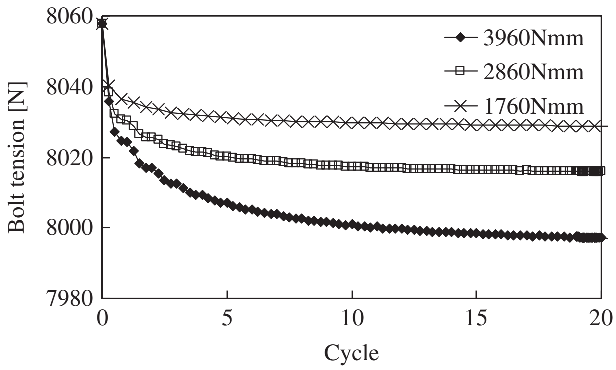

Fig. 9a. Bolt tension for the case applied torque is set smaller than T_{sl} for $\mu_s = 0.10$ (4350 N).

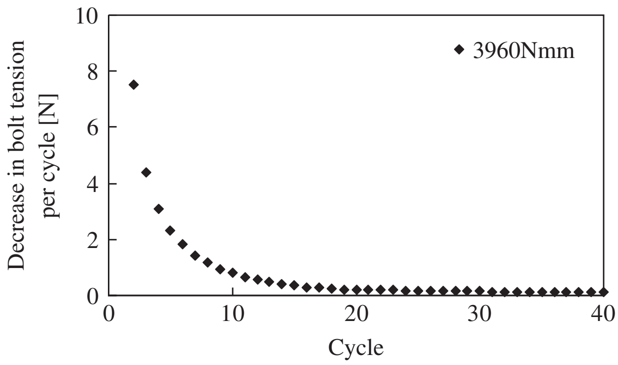

Fig. 9b. Decrease rate of bolt tension for the case of $T = 3.96 \times 10^3$ N mm.

4.3. Joint behavior in the case complete slip on the contact surfaces does not occur

It is known that slight loosening progresses even if the bearing surface does not undergo complete slip in the case of transverse loading. Here, it is investigated whether such slight loosening also progresses in the case of rotational loading. This corresponds to the case in which the rotation angle of the movable plate does not reach θ_{cr}. FEM analyses were performed under the condition of $\mu_s = 0.10$, $\mu_w = 0.10$, and three values of applied torque: 91%, 66%, and 40% of the loosening torque of the thread surface T_{sl} (3.96×10^3 N mm, 2.86×10^3 N mm, and 1.76×10^3 N mm, respectively).

The torque–rotation angle relation of the movable plate during the 20th loading cycle is shown in Fig. 7 and variation in the rotation angle of the bolt for the case of $T = 3.96 \times 10^3$ N mm is shown in Fig. 8. Only the sloped region appears in the torque–rotation angle relation. As to the variation in the rotation angle of the bolt, the bolt head rotates while sticking to the movable plate and only slight rotation occurs in the loosening and tightening directions on the thread surface because

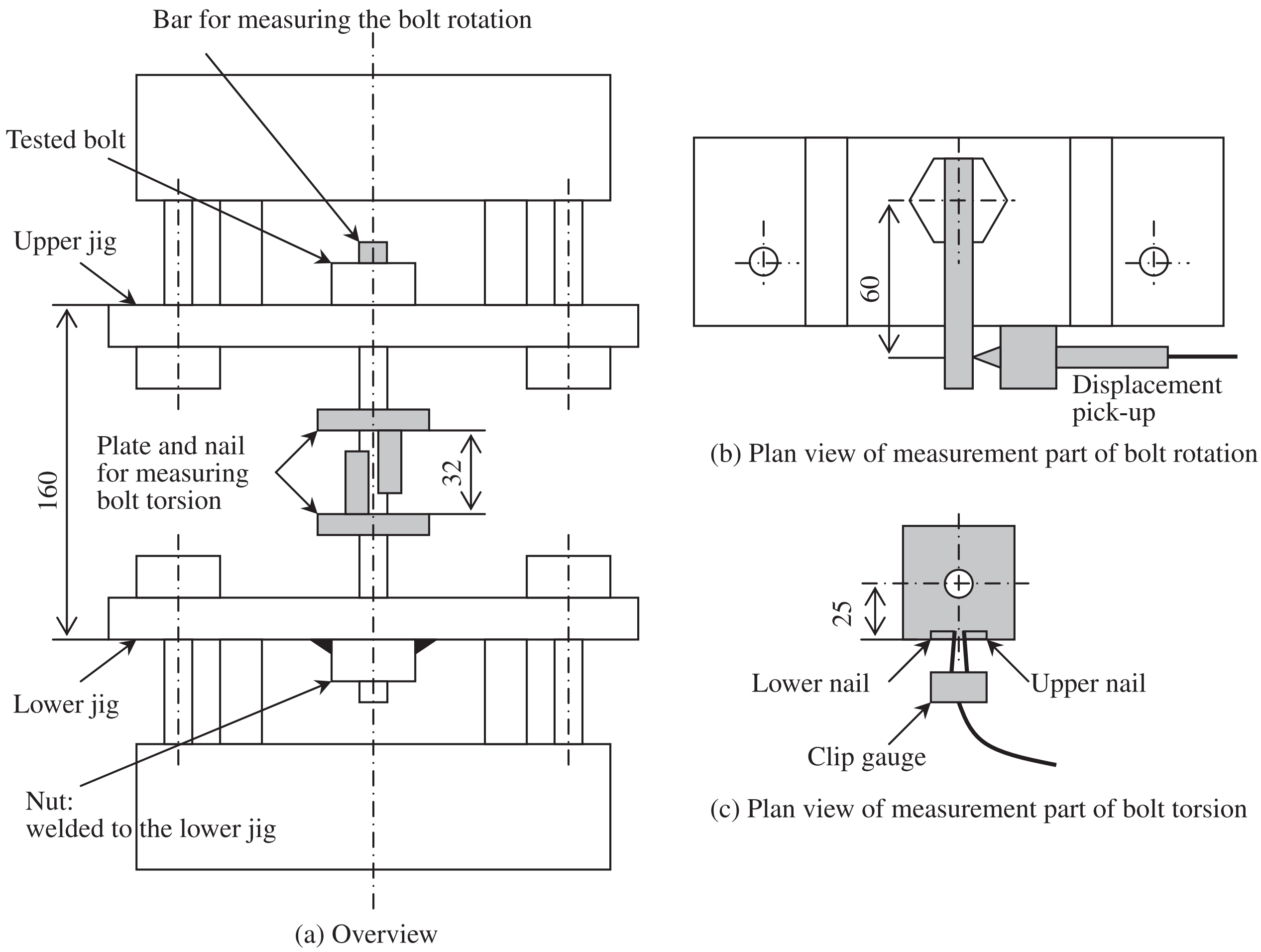

Fig. 10. Experimental set up for loosening due to rotational load.

the bearing surface is in a state of complete stick while the stick region shrinks gradually on the thread surface. Variation in the bolt tension is shown in Fig. 9a. It can be seen that the decrease in bolt tension is large in the early cycles as the applied torque is large. However, it is expected that the bolt tension settles to a value as the cycle progresses in every case. The decrease rate of bolt tension (the decrease from the previous cycle) for the case of $T = 3.96 \times 10^3$ N mm is shown in Fig. 9b. It can be seen that the decrease rate converges to 0. Therefore, it is supposed that the decrease will stop. It is confirmed that the difference in the rotation angle on the thread surface, which corresponds to the decrease in bolt tension, in the loosening and the tightening processes becomes negligible as the loading cycles progresses, though the angle in the loosening process is larger than that in the tightening process in the early cycles. Therefore, it can be said that loosening does not progress if the contact surfaces do not enter the state of complete slip.

5. Loosening test

A loosening test was conducted using a hydraulic testing machine (MTS tension/torsion) in order to verify the loosening mechanism explained by FEM. The set up of the test is shown in Fig. 10. The nominal diameter of the used bolt and nut was M14 and the grip length was set to 160 mm. The joint has a standard engaged thread length. The nut is welded to the lower jig so that only the bolt can rotate. A rectangular bar was attached to the bolt head and its displacement was measured using a displacement sensor (LVDT with 2 mm range) to obtain the rotation angle of the bolt head. The torsion of the bolt axis was measured as the relative rotation angle of the two plates with a nail attached to the bolt axis at a right angle to the bolt axis using a clip gauge (Instron 2.5 mm). The bolt tension and applied torque were measured by the load cells (MTS axial-torque cell) that the test machine is equipped with.

The bolt and nut pairs were cleaned using toluene and dried. Then, machine oil (Castrol Magna GC32) was applied on the thread and the bearing surfaces as lubricant. The bolt tension was set to 8 kN as tensile loading by the test machine. The amplitude of the relative rotation angle applied to the jigs was set to 0.6° and the frequency was set to 1 Hz. This condition produced the flat region in the torque–rotation angle relation diagram.

The test results can be explained as follows. Firstly, the torque–rotation angle relation of the movable plate for three cycles is shown in Fig. 11. This figure shows a hysteresis loop that involves sloped and flat regions. Next, variation in the rotation angle of the bolt is shown in Fig. 12. The variation shows the same tendency as the FEM result shown in Fig. 4a. That is, the thread surface undergoes a complete slip and the bolt rotates while sticking to the movable plate in the loosening process. On the other hand, the bearing surface undergoes a complete slip and the bolt does not rotate in the tightening processes. This indicates that the maximum torque in the loosening process corresponds to T_{st} while that in the tightening

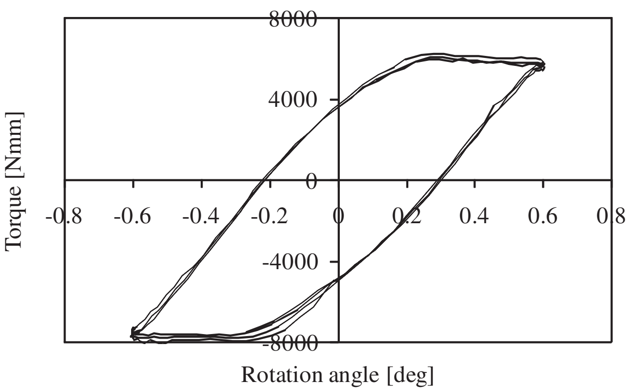

Fig. 11. Torque–angle relation (experiment).

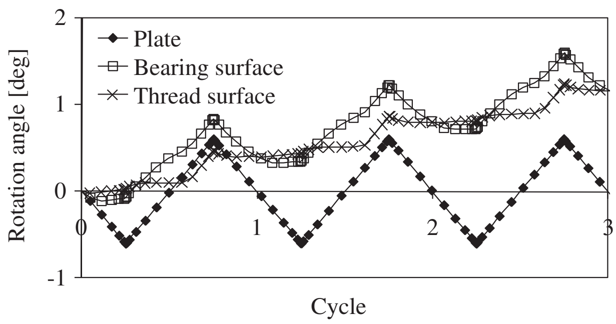

Fig. 12. Rotation angle (experiment).

process corresponds to T_w in the torque–angle relation shown in Fig. 11. The coefficient of friction on the thread surface and that on the bearing surface were calculated as $\mu_s = 0.15$ and $\mu_w = 0.12$ using Eqs. (1) and (3), respectively. Under these conditions, $T_{sl} < T_w < T_{st}$ holds. From the above comparison of macroscopic behavior such as the bolt rotation angle, it is confirmed that the loosening mechanism obtained by the experiment is reproduced by FEM qualitatively. The mechanism will be elucidated more precisely by the observation of the contact behavior in the future work.

6. Conclusions

The self-loosening mechanisms of a bolted joint subjected to a rotational load have been investigated using three-dimensional FEM. Sakai's theory regarding the condition of the initiation and the progress of loosening was verified. Loosening occurs if the rotation angle applied to the movable plate reaches a critical value θ_{cr} and the thread surface undergoes a complete slip. If not, the torque–rotation angle relation becomes linear. In addition, loosening progresses if $T_{sl} < T_w < T_{st}$ holds, where T_{sl}, T_{st}, and T_w are the loosening and the tightening torque of the thread surface, and the slip torque of the bearing surface, respectively. In this case, bolt tension decreases in proportion to the rotation angle of the movable plate during complete thread-surface slip in the loosening process while the bolt tension does not change during complete bearing-surface slip in the tightening process. If the coefficient of friction on the bearing surface is small compared to that on the thread surface and $T_w < T_{sl} < T_{st}$ holds, self-loosening does not progress because only the bearing surface undergoes a complete slip in both the loosening and tightening processes. Also, if the coefficient of friction on the bearing surface is large compared to that on the thread surface and $T_{sl} < T_{st} < T_w$ holds, self-loosening does not progress because the difference in the thread rotation angle in those processes is negligible.

A loosening test was carried out using a tension/torsion testing machine in order to verify the loosening mechanism shown by FEM analysis. It was confirmed that the loosening progressed by showing the same variation in the rotation angle of the bolt as that shown by FEM when machine oil was applied on the thread and the bearing surfaces (see Fig. 10).

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