

Loosening Evaluation of Bolt-Nut Fastener Under Transverse Cyclic Loading

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In this paper, we evaluate the sliding and the loosening behavior of thread joints (M16 bolt-nut fastener) under transverse loading. First, the critical relative slippage (Scr), less than the displacement in which the thread joints can keep the fastening, are obtained by the cyclic loading tests. Then, this critical relative slippage is estimated according to the theoretically obtained equation by considering the bending deformation of bolt and the geometrical constraint condition. The inclination compliance (kw) of the bolt head used in this equation is evaluated by comparing the experimental result with the corresponding analytical one. In consideration of the nonlinearity of kw with respect to the bolt axial tension, the Scr is well estimated by this equation.

Key words: thread joint, bolt-nut fastener, sliding and loosening behavior of bolt, transverse loading, critical relative slippage, inclination compliance of bolt head.

1. INTRODUCTION

Considering the efficient productivity and maintainability, most of machine and product has many joints (e.g., fastening, welding and adhesive joints). In particular, the thread joint has been frequently used for these purposes as a machine element. However, many troubles, such as loosening of bolted joints or fatigue failure of a bolt, are often experienced. Much attention must be paid to the improvement of the strength and the reliability of the thread joints. It is generally said, that the fastening axial force rapidly decreases by the rotation

loosening of nuts if the relative slippage on the interfaces between the nuts and the fastened body goes beyond a certain critical limit [1, 2]. For example, the thermal expansion due to temperature change between jointed members may cause this kind of problem. Another reason for these troubles is that the deformation behavior and strength of the machine are not evaluated sufficiently in the CAE analysis, because of imperfections in the database of mechanical properties of these joints.

The aim of the present research is to construct an industrially available database, including equivalent rigidity and critical relative slippage of these joints for the CAE process. As the first step, in this paper, we present the investigated results of the sliding and the loosening behavior of thread joints (M16 bolt-nut fastener) under the transverse cyclic loading condition. Further, the critical relative slippage (S_{cr}) that prescribes the upper limit for preventing the loosening behavior is experimentally obtained from cyclic loading test. And the inclination compliance (kw) that represents the pseudo-rigidity of the bolt head portion is evaluated using the theoretically constructed equation and the experimental result.

2. SLIDING BEHAVIOR OF THE THREAD JOINT

The sliding behavior of the thread joint under transverse loading is shown in Fig. 1. The deformation behavior of the thread joint mainly depends on the amount of transverse loading given to the joint. When the load is low, the bolt and fastened components (two plates) are deformed as one body (Fig. 1a).

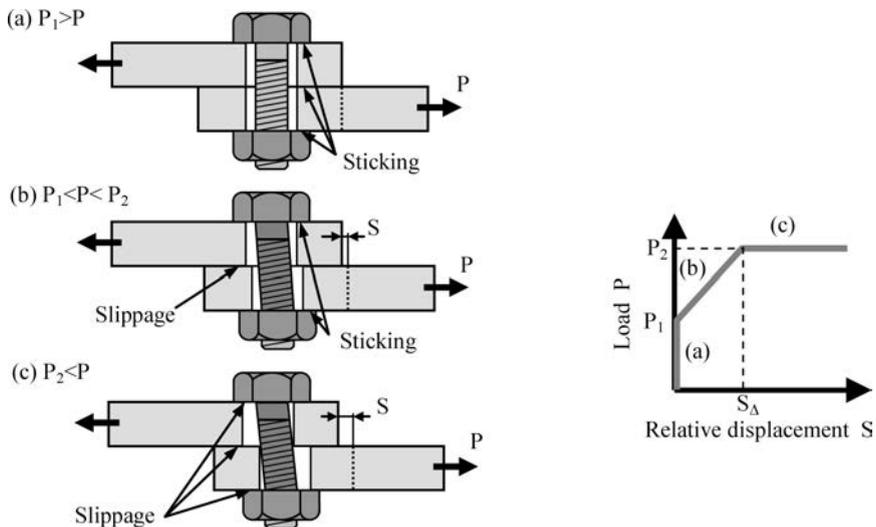


FIG. 1. Behavior of the thread joint (bolt-nut fastener) under different load conditions.

On the other hand, relative sliding is generated at the interface between the upper and lower plates, when the load becomes greater than the frictional force (the number of the bolts $n \times$ the friction coefficient $\mu \times$ the initial bolt axial tension F). However, when relative slippage S between upper and lower plates is small, the relative slippage is absorbed by the bending deformation of the bolt and does not generate the relative sliding between the bolt head and the fastened component (Fig. 1b). The relative displacement increases with the increase in the load. The relative sliding is generated at the interface between bolt head and fastened component, when the relative displacement exceeds the critical relative displacement S_{Δ} (Fig. 1c). Then, the bolt loosening due to its rotation is inevitable and thus the axial tension decreases.

3. CRITICAL RELATIVE SLIPPAGE SCR

Concerning the loosening of the thread due to its rotation under transverse loading, YAMAMOTO and KASEI *et al.* proposed an equation which evaluates the critical relative slippage using the experimental result [3, 4]. Critical relative slippage Scr that prescribes the upper limit for preventing the loosening behavior is dominated by flexural rigidity of the bolt and the inclination compliance k_w that represents the pseudo-rigidity at the bolt head portion. The Scr is estimated by the following equation, which is derived from the bending deformation of the simple beam instead of from the bolt [5]; as shown in Fig. 2. The Scr value is proportional to the bolt axial tension.

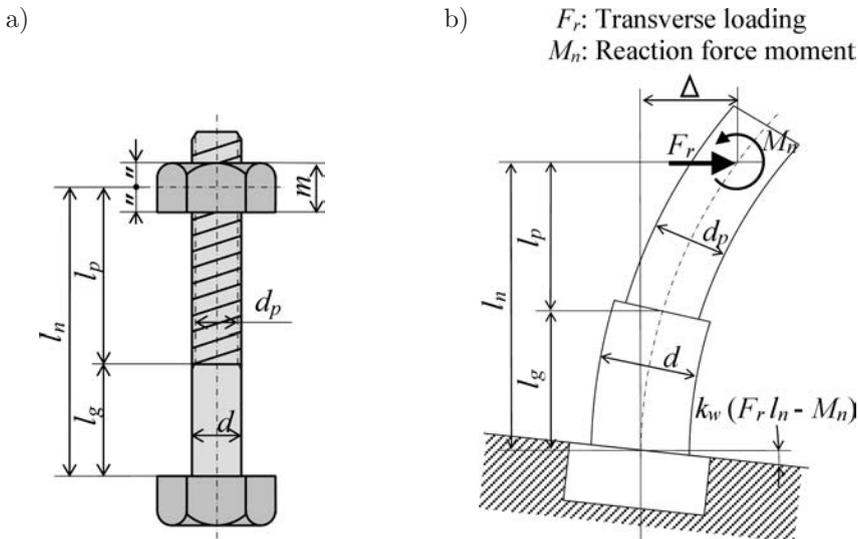


FIG. 2. Estimation of critical relative slippage Scr by using the simple beam model: a) symbolic dimensions of a bolt-nut joint structure, b) deflection of a bolt by transverse loading.

$$(3.1) \quad Scr = 2\Delta = 2F \left[\mu_w \left(\frac{l_g^3}{3E_b I_g} + \frac{l_p^3}{3E_b I_p} + \frac{l_g l_p l_n}{E_b I_g} + k_w l_n^2 \right) - \left(\frac{m}{4} \right) \left(\frac{\mu_s}{\cos^2 \alpha} \right) \left(\frac{l_g^2}{2E_b I_g} + \frac{l_p^2}{2E_b I_p} + \frac{l_g l_p}{E_b I_g} + k_w l_n \right) \right],$$

F – Bolt axial tension, μ_w – frictional coefficient of the interface between bolt head and fastened component, μ_s – frictional coefficient of the threaded interface, k_w – inclination compliance of the bolt head portion, E_b – longitudinal modulus of elasticity of the bolt, I_g , I_p – moment of inertia of the cross-sectional area of the bolt, α – half-thread angle, $\cos 2\alpha = 0.75$.

4. EXPERIMENTAL CONDITIONS

4.1. Bolt-nut fastener

Flat plates made of medium carbon steel were fastened with one bolt as illustrated in Fig. 3. The plate has a 64 mm width, 157 mm length and 9 mm thickness. Both plate surfaces were ground in the loading direction. The commonly used bolt made of carbon steel was used for the fastening, whose specification was M16×2(pitch)×55(nominal length) and thread length 40 mm. The specifications of the M16 bolt are given in Table 1. The thread joint and sensors are also shown in the figure. The bolt axial tension is measured by the strain gauge embedded in the bolt.

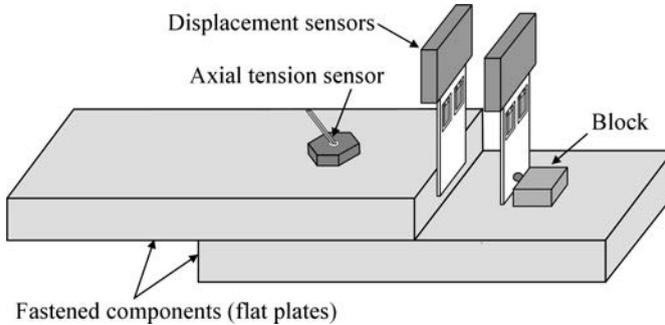


FIG. 3. Bolt-nut fastener and sensors.

Table 1. Specifications of M16 bolt.

Nominal diameter [mm]	Strength classification	Ultimate tensile strength [MPa]	Proof stress [MPa]	Pitch [mm]	Effective sectional area [mm ²]	Standard axial tension [kN]
M16	4.8	392	314	2	157	34.5

4.2. *Experimental setup and procedure*

The fatigue testing machine with a hydraulic cylinder was used in order to give transverse cyclic loading in the bolt axis direction. The apparatus was composed of a hydraulic pump, servo valve, servo controller, function generator, load cell, and recording device.

Quasi-static or cyclic transverse load was applied to the bolt-nut fastener as shown in Fig. 3. Transverse load, bolt axial tension and displacement of two plates were measured by sensors and a load cell. The displacement of the lower plate was measured by using small block bonded to it. The relative displacement between the plates was also measured.

In the quasi-static loading test, the static loading (tension) was given to the bolt-nut fastener which were fastened by various bolt axial tension (5 types of 35 kN, 30 kN, 25 kN, 20 kN, and 15 kN). The critical transverse load in which sliding was generated between the bolt head and the fastened component was examined.

The cyclic loading (tension-compression) test was carried out. The bolt axial tension was the same condition as the quasi-static loading test. The sinusoidal wave load (displacement) of 1 Hz was applied to the bolt-nut fastener, at most 10,000 times. When the decrease in the bolt axial tension became rapid, the cyclic loading was stopped. The displacement given to the bolt-nut fastener was changed in accordance with the bolt axial tension in order to obtain a critical relative slippage Scr , less than the displacement in which the thread joints can keep the fastening.

5. EXPERIMENTAL RESULTS

5.1. *Quasi-static loading test*

The relationship between the load and relative displacement of a pair of plates is shown in Fig. 4. In result of the tension loading, the difference between the various bolt axial tensions was compared. It is clear that the lower the bolt axial tension, the lower the transverse load which generates sliding at the interface between the bolt head and fastened component in Fig. 4. The friction coefficient of thread joints used in this research was about 0.19.

The relative displacement that is the relative sliding length was monitored by the displacement sensors during experiment as shown in Fig. 3. When the sliding length increases without an increase of tension, the slippage at the interface between bolt head and fastened component takes place as shown in Fig. 4. This is the critical relative displacement and corresponds to a transition point from a sticking to a sliding condition. It is however difficult to measure it precisely, because a small change in experimental conditions affects much of the result. In

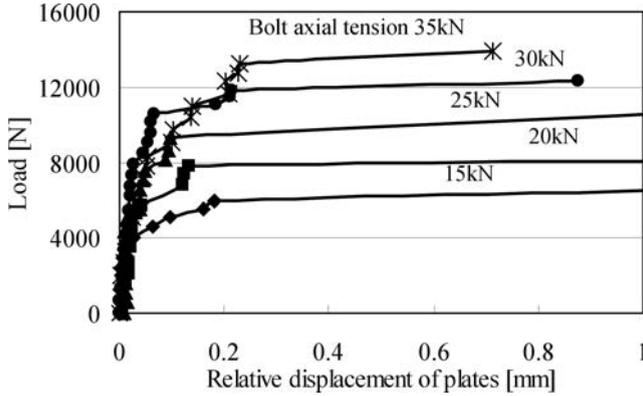


FIG. 4. Dependence of transverse load on relative displacement.

this study, the change of bolt axial tension by cyclic loading was examined, and the critical relative slippage Scr under which the thread joint can keep fastened was obtained from the relation between the amplitude of the displacement and bolt axial tension in cyclic testing.

5.2. *Cyclic loading test*

The bolt axial tension decreases with the number of cycles as shown in Fig. 5, for various displacement conditions in which the initial bolt axial tension is 15 kN. The decreasing speed in the axial tension is estimated as dF/dN . The dF/dN value was calculated by the change in the bolt axial tension in the range from 500 to 1000 cycles in which the bolt axial tension is regarded as almost linear in all experiments.

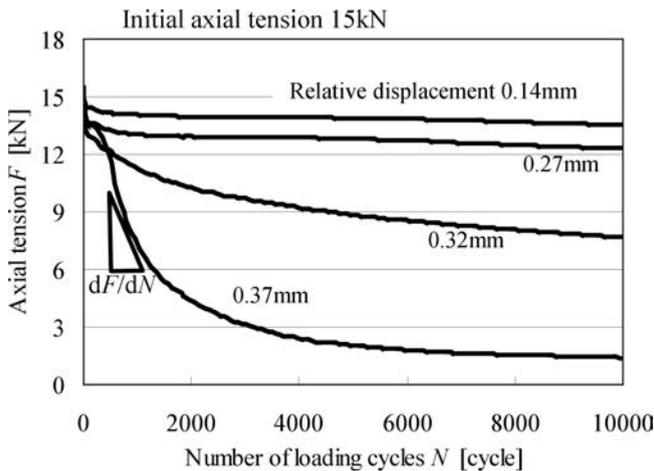


FIG. 5. Dependence of axial tension on the number of loading cycles.

The bolt axial tension decreases rapidly as the relative displacement becomes larger, where loosening of the bolt due to its rotation occurs. The loosening speed of the bolt depends on the number of loading cycles and relative displacement.

In order to determine the critical relative slippage Scr , the loosening speed dF/dN with the relative displacement is drawn in Fig. 6 for each bolt axial tension. The relative displacement Scr , at which the loosening speed drastically changed, was determined and whose value is depicted in the figure.

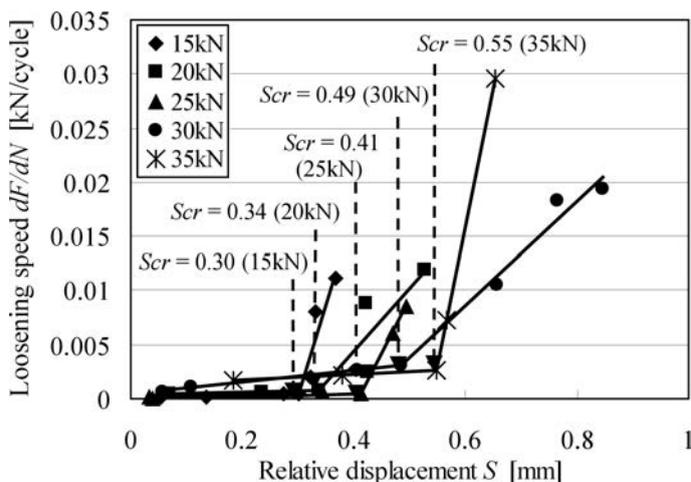


FIG. 6. Dependence of dF/dN on the relative displacement.

By substituting the determined Scr in Eq. (3.1) for the case with a bolt axial tension of 35 kN, the inclination compliance kw of the M16 bolt head is calculated to be $3.94 \times 10^{-5} \text{ (kN}\cdot\text{mm)}^{-1}$. However, the lower the bolt axial tension becomes, the larger the value of kw varies, because of the decrease of the apparent or equivalent rigidity of the thread joint. In the low fastening force region, the contact surface pressure at the threaded interface and the interface between the nut and the fastened component decreases, and then the bolt head tends to incline. The contact surface pressure over a certain value is necessary such that the constraint force at the thread interface becomes sufficient to avoid the inclination of the bolt. The Scr value is proportional to the bolt axial tension F , such that kw takes on a constant value in the high fastening force region [4]. On the other hand, it was reported that kw was inversely proportional to the bolt axial tension F in the low fastening force region, and took the constant value over some fastening force [6]. The behavior of the bolt screwed to the thick plate where the nut was not used was investigated in these papers. Therefore this estimation method was applied to the bolt-nut fastener. As for

the thread joints used in the experiment, the kw of M16 bolt head was evaluated by the following equations, as demonstrated in Fig. 7.

$$(5.1) \quad kw = (84.4/F) \times 10^{-5} \text{ (kN} \cdot \text{mm)}^{-1} \quad \text{for } F < 21.4 \text{ kN,}$$

$$(5.2) \quad kw = 3.94 \times 10^{-5} \text{ (kN} \cdot \text{mm)}^{-1} \quad \text{for } F \geq 21.4 \text{ kN.}$$

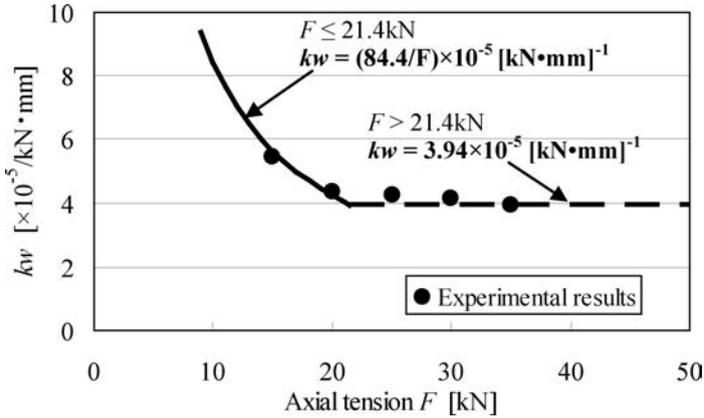


FIG. 7. kw values obtained by experiment and their corresponding fitting curve.

Equation (5.1) is available for conditions with a low bolt axial tension less than 21.4 kN. This bolt axial tension (21.4 kN) shows the minimum value at which kw can be taken as a constant value. Figure 8 describes the two Scr trend lines by Eq. (3.1), in which kw is calculated by Eqs. (5.1) or (5.2). By applying these kw relations, we can estimate the Scr for arbitrary bolt axial tension by Eq. (3.1).

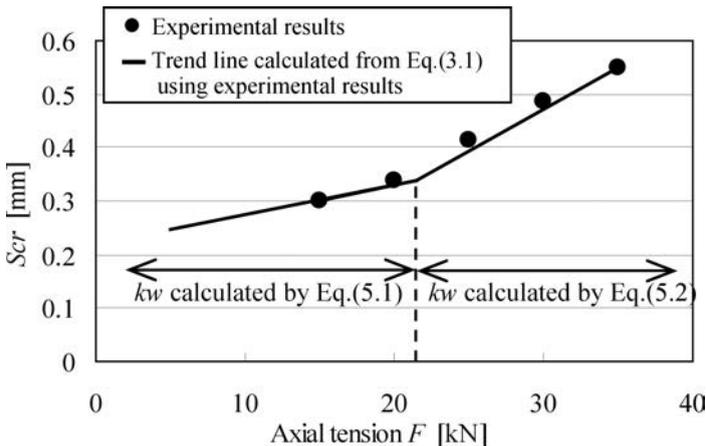


FIG. 8. Estimated Scr by experiment.

In the high fastening force region, it was reported that the kw value of the M10 and M22 bolted joint was $1.61 \times 10^{-4} \text{ (kN}\cdot\text{mm)}^{-1}$ [4] and $1.4 \times 10^{-5} \text{ (kN}\cdot\text{mm)}^{-1}$ [6] respectively. The inclination compliance, which is the reciprocal of rigidity, becomes small, because the rigidity increases with bolt diameter and the bolt head portion does not show the tendency of inclination. The kw value of M16 bolt-nut fastener was estimated to be $3.94 \times 10^{-5} \text{ (kN}\cdot\text{mm)}^{-1}$ in the present study. Thus the result seems convincing.

These Scr and kw which are the result in the present study can be applicable as an appropriate deformation threshold of the bolt-nut fastener under the transverse loading condition. The experiment for the various bolt axial tensions and amplitudes of the displacement will be carried out to improve on the accuracy of its value in the future, especially for the transiting bolt axial tension in which kw becomes constant.

6. CONCLUSIONS

The transverse loading test for a thread joint (M16 bolt-nut fastener) was carried out, and its sliding and loosening behaviors were examined. The main results are summarized as follows:

1. The critical relative slippage Scr less than the displacement, in which the thread joints can keep the fastening, decreases with a decrease of the bolt axial tension.
2. By considering the nonlinearity of inclination compliance kw of the bolt head, the critical relative slippage Scr is well determined even for cases with low bolt axial tension.

Characteristics for the loosening of various bolt-nut fasteners, including the results of this study, are constructed as an industrially available database and contribute to the accuracy improvement of CAE analysis.

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