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Loosening-resistance evaluation of double-nut tightening method and spring washer by three-dimensional finite element analysis

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ABSTRACT

The mechanisms of loosening-resistance components are investigated within the framework of the three-dimensional finite element method (FEM). In this paper, we have evaluated the ability of double-nut tightening method (DN) and spring washer (SW) to resist self-loosening due to transverse loading. We have found that if locking state is properly achieved in the tightening process, DN shows significant loosening resistance regardless of the magnitude of locking force. It was observed in this case that thread surface on the upper nut retains stuck state even if bearing-surface undergoes complete slip. However, if the locking process is not performed properly, the ability to resist loosening completely disappears. On the other hand, it is shown that SW accelerates loosening rotation of nut. The stuck area on the contact surfaces is reduced to two corner edges of the SW and the rotational force around these edges thus drastically leads to loosening before complete bearing-surface slip.

1. Introduction

Bolted joints are widely used in mechanical structures due to the joints' ease of disassembly for maintenance and their relatively low cost. However, vibration-induced loosening due to dynamic loading has remained unsolved, and fatal accidents due to joint loosening still frequently take place every year in Japan. As a response to these problems, numerous kinds of loosening-resistance components have been developed and used. Double-nut tightening method is a classical one. It is well-known that the correct tightening procedure is necessary to bring out its potential performance. Although washers such as plain washers and spring washers also have been used in many industries in attempts to resist bolt loosening, it has been shown experimentally that their effect on preventing loosening rotation does not appear in every case [1–4].

Three-dimensional finite element models considering the helical profile specific to threads can represent the loosening of bolted joint. In previous work [5], the authors performed FE analysis on bolt loosening due to external loading perpendicular to the bolt axis (transverse loading) and obtained close qualitative agreement with the experimental results reported by Yamamoto and Kasei [6]. In addition, we investigated the mechanisms of a self-loosening prior to the complete bearing-surface slip (loosening rotation due to micro bearing-surface slip) suggested by Kasei [7] and Pai and Hess [8] and showed that a small degree of loosening occurs when the transverse load reaches about 50–60% of that of bearing-surface slip [9]. This modeling method using FEM enables us to examine the effects of loosening-resistance components on the prevention of loosening.

In the present study, the effects of double-nut tightening method (DN) and a spring washer (SW) on loosening resistance were investigated using the three-dimensional finite element modeling method. We focus on the loosening due to both complete and micro bearing-surface slips in this study.

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2. Analysis method

2.1. Overview of finite element model

Historically, Junker's loosening apparatus, in which roller bearings are placed between a movable top plate and a fixed plate to minimize sliding friction, has been widely used to observe loosening behavior [10]. In the present study, we model part of Junker's loosening apparatus which includes a bolted joint employing a loosening-resistance component, and examine the effect by observing the progress of loosening rotation and the decrease in bolt tension. The FEM model for reproducing Junker's loosening apparatus is shown in Fig. 1. We use a general-purpose finite element method software, ANSYS 10.0. Details of modeling are shown in [5]. The model reproduces a helical profile of the internal and external threads, but detailed shapes such as the curvature of the bottom of thread are not taken into account since a detailed evaluation of stress distribution is beyond the scope of the present study. The bolt–nut size is M10, and the grade and position of the crossover is 6H/6g (expressed in terms of the Japanese Industrial Standards). Because the friction between the movable top plate and the fixed plate can be ignored in the loosening apparatus, only part of the movable plate is modeled, and the displacement of the bottom of the movable plate in the vertical (y) direction is fixed.

Contact elements are used to incorporate contact behavior at all the interfaces such as between the mating threads, under the nut bearing-surface, and so on. In this model created using ANSYS, contact element pairs TARGE170 and CONTA174, which realizes surface–surface contact between three-dimensional objects and can deal with the Coulomb friction, are used. The pure penalty method is employed as a contact algorithm. To reduce calculation costs, bolt tension is generated by allowing initial interference between the movable plate and the lower nut (in the case of a DN joint), or between the movable plate and the washer (in the case of a SW joint). The transverse load is applied to the end surface of the movable plate as constrained displacement or force. A displacement-constrained boundary condition is employed in order to observe the loosening due to complete bearing-surface slip, while a force-constrained boundary condition is employed to observe the loosening due to micro bearing-surface slip. The Young's modulus and Poisson's ratio for all the components (bolt, nut, SW, and movable top plate) are 205 GPa and 0.3, respectively. The friction coefficient of the contact surfaces is set to 0.15. The performed FEM analysis is quasi-static and elastic. Geometric nonlinearities are taken into account.

Detailed analysis conditions for each case of DN and SW joints are explained in the sections below. For each case, a progress of loosening is compared to the case of a standard joint. The progress in loosening is evaluated from two viewpoints. One is the relative rotation angle of nut with respect to bolt (loosening rotation angle). The other is the decrease in bolt tension.

2.2. Double-nut (DN) joint

Two methods are well-known to set up the double-nut joint, that is, the upper nut rotation method and the lower nut reverse rotation method. This study is intended for the latter. After the processes of lower nut reverse rotation method, thread of the lower nut comes in contact on the surface opposite to the one that is in contact in the standard tightening process. This state is called as "locking state", and the force produced on the thread of lower nut is called as locking force. The details of FEM analysis for the tightening process are shown elsewhere [11]. Here, in order to reduce calculation costs, bolt tension and locking force are generated by using an initial interference scheme. The bolt tension and the locking force are generated by the interference between the movable plate and the lower nut and that between the upper nut and the lower

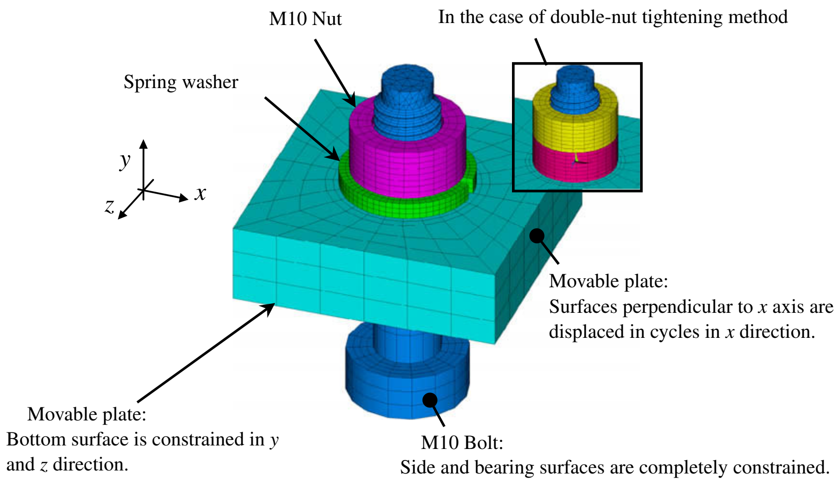

Fig. 1. Finite element model for loosening analysis of bolted joint.

nut, respectively. At the locking state, the lower surface of the lower nut thread is in contact with the upper surface of the bolt thread. And the thread of the upper nut supports both bolt tension and locking force. Bolt tension is adjusted to 10 kN. Four kinds of locking states are employed. Case 1 has a high locking force of 8.8 kN, while Case 2 has a low locking force of 1.1 kN. Although Case 3 is in the locking state, its locking force is close to zero. Case 4 is not in the locking state, which means that there is a gap between the thread of the lower nut and that of the bolt. Therefore, the thread of the lower nut is not loaded at all and the thread of the upper nut supports only the bolt tension. Only the loosening due to complete bearing-surface slip is investigated since no loosening occurs in the case of micro bearing-surface slip. The amplitude of the movable plates' transverse displacement is set to 0.3 mm.

2.3. Spring washer (SW) joint

The general-use SW categorized in JIS B1251 is modeled. In order to reproduce the spring force of a SW, the initial stress is applied to the flat C-shaped volume, which has a slit of 10°. The detailed modeling process is described according to Fig. 2. As shown in step (a), while one end of the SW is fixed, the other end is displaced by 2.5 mm along the normal direction. In the next step (b), the shape is updated to the deformed shape and the developed stress is cleared. In step (c), the resulting updated shape is compressed so that its deformed shape becomes flat like the initial shape shown in step (a). In step (d), the developed stress is output as initial stress. In step (e), the recorded initial stress is given to the initial flat C-shaped volume. The spring force becomes about 1 kN. Bolt tension is set to 10 kN. Both complete and micro bearing-surface slips are investigated. In the former case, the amplitude of the movable plates' transverse displacement is set to 0.4 mm. Two vibration directions (x- and z- directions) are investigated.

3. Analysis results

3.1. DN joint loosening

The relationships between the applied load and the transverse displacement are shown in Fig. 3 ((a) Cases 1–3 and (b) Case 4). They show hysteresis loop. The loops for Cases 1–3 consist of a slope and a flat region, and it is seen that the slope is steeper as the locking force is larger. On the other hand, the loop for Case 4 consists of two kinds of slopes and a flat region. The contact states at a point of complete bearing-surface slip, which corresponds to the flat region in Fig. 3, are shown in Fig. 4 for each case. It is observed that thread surface of the upper nut retains stuck state, while it undergoes complete slip in Case 4. The complete thread-surface slip occurs before the complete bearing-surface slip in Case 4 and leads to the change of slope in the hysteresis loop.

The variations in bolt tension during three vibration cycles are shown in Fig. 5 ((a) Cases 1–3 and (b) Case 4). And the variations in locking force relative to the initial value are shown in Fig. 6 ((a) Cases 1–3 and (b) Case 4). It is found that the variation in bolt tension shows a half-cycle period. In addition, it can be seen that the variation is larger as the locking force is smaller. Judging from Fig. 6, it can be considered that the variation in bolt tension originates from the variation in locking force. In Case 4, although there is a gap between the thread of the lower nut and the bolt in its tightening process, it is found that locking force develops due to the applied load.

A significant decrease in bolt tension is detected only in Case 4. Even though complete bearing-surface slip occurs, there is no significant decrease in Cases 1–3. The amounts of the decrease during the third cycle in Cases 1–4 are 0.65, 2.7, 4.7, and 220 N/cycle, respectively.

These results indicate that if the locking state is properly achieved, the double-nut tightening method completely stops the loosening regardless of the magnitude of the locking force. However, if locking state is not properly achieved, the loosening-resistance performance completely vanishes. This tendency agrees well with Yamamoto and Kasei's experiments for the effect of locking state on the progress in loosening [12].

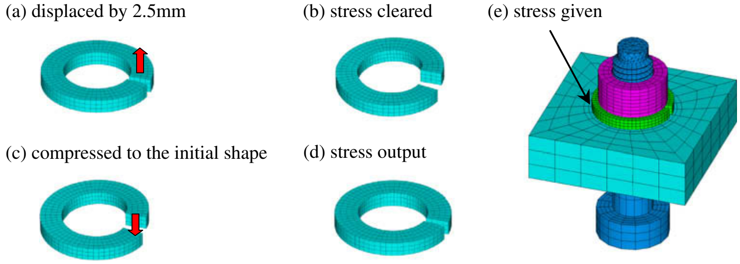

Fig. 2. Modeling procedure for spring washer.

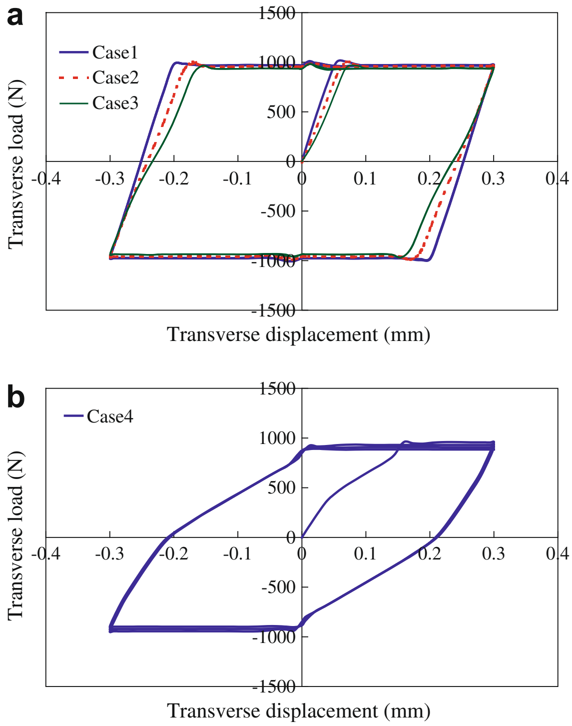

Fig. 3. Relation between transverse load and displacement: (a) Cases 1–3 and (b) Case 4.

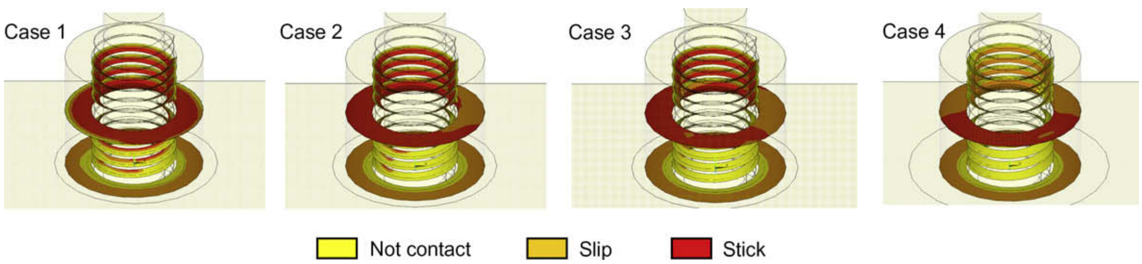

Fig. 4. Contact states for four cases when lower nut bearing-surface completely slips.

3.2. SW joint loosening due to complete bearing-surface slip

The loosening rotation angles during three vibration cycles are shown in Fig. 7. It is observed that the loosening rotation of the SW joint proceeds faster than that of the standard joint. It can be also said that there is no significant dependence on the vibration directions (x and z directions). Two effects are considered to increase loosening rotation. One is that the torsion of the bolt axis increases because the grip length of the joint is increased by adding a SW under the nut, as discussed in the case with a plane washer [13]. The other is that the pressure distribution of a SW is concentrated on the corner edges. The latter effect is discussed in detail below.

The relationship of the applied load and the transverse displacement (x-direction) is shown in Fig. 8 accompanied by the case of standard joint. It is widely accepted that a load–displacement curve consists of three kinds of slopes: a steep slope (A), a gradual slope (B), and a flat slope (D). However, it can be seen that an extremely gradual slope (C) is added in the SW joint.

Schematics of the contact state during x-direction vibration are shown in Fig. 9. Symbols of A–D correspond to those denoted in Fig. 8. First, in slope A, partial slip occurs both on the thread and the SW surfaces. Secondly, in slope B, the entire thread surface undergoes complete slip. At the end of slope B, the stuck regions on the SW surfaces are reduced around three or four edge points. Next, in slope C, the stuck regions are further limited to only two edge points. The rotation of the SW around these stuck edge points occurs at this stage. Details of the mechanism of this rotation are discussed later. Finally, in the former part of slope D, complete slip occurs both on the thread and the SW surfaces. In the latter part of slope D, the thread surface regains a stuck state.

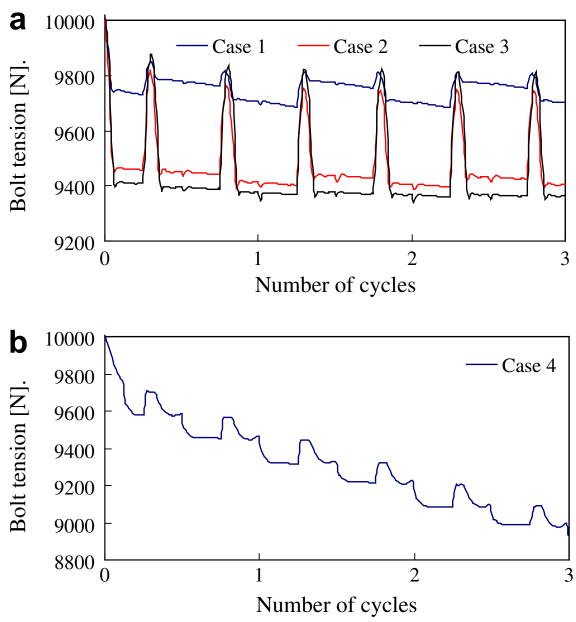

Fig. 5. Variations in bolt tension: (a) Cases 1–3 and (b) Case 4.

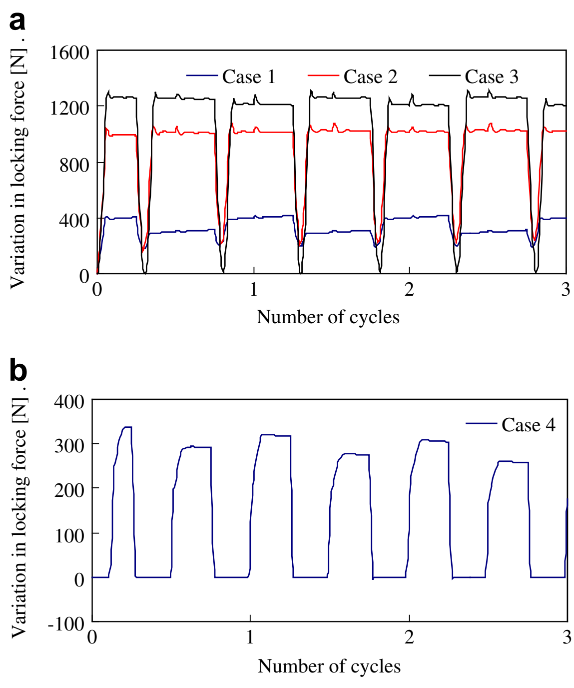

Fig. 6. Variation in locking force: (a) Cases 1–3 and (b) Case 4.

The progress in the rotation angles of the nut and the SW in the case of x vibration are shown in Fig. 10. It is found that the rotation direction depends on the vibration direction. The SW rotates in the loosening direction during stage C of $+x$ displacement while it rotates slightly in the tightening direction during that of $-x$ displacement. This reverse rotation is caused by rotation around two edge points as illustrated in Fig. 11. Depending on the vibration direction, the rotation direction of the SW changes. Due to its effect, nut rotation during $+x$ displacement (around cycle 0, 1, and 2) becomes larger than that in the $-x$-direction (around cycles 0.5, 1.5, and 2.5). Particularly, the nut rotation proceeds mainly during stage C while it does not proceed as much during stage D in which complete bearing-surface slip occurs. This indicated that the SW joint could loosen more than the standard joint even prior to the load of complete bearing-surface slip.

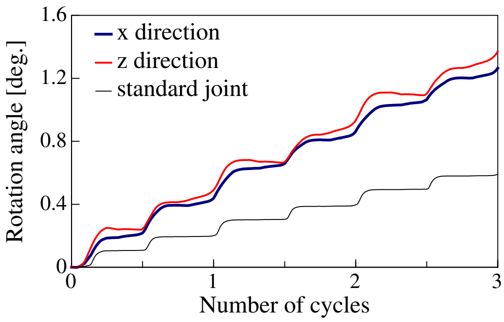

Fig. 7. Loosening rotation angle of the nut.

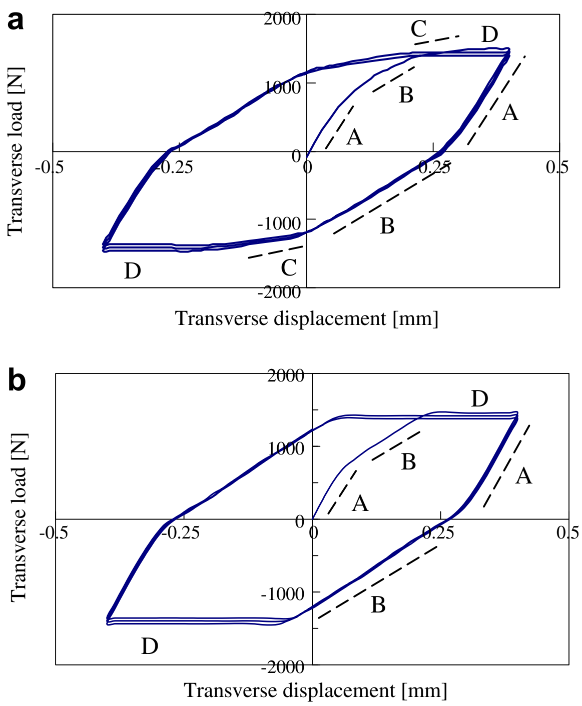

Fig. 8. Relation between transverse load and displacement: (a) SW joint and (b) standard joint.

3.3. SW joint loosening due to micro bearing-surface slip

The progresses in loosening rotation angle caused by the 1000 N transverse load are shown in Fig. 12. It is observed that the loosening rotation of the SW joint proceeds faster than that of the standard joint as the case of complete bearing-surface slip. However, the vibration in z-direction causes faster loosening rotation in this case than that in x-direction does. In particular, SW joint shows significant loosening rotation at the beginning of the vibration.

The rates of the loosening rotation angle under various transverse loads, which are less than critical for complete bearing-surface slip, are plotted in Fig. 13. Here, the transverse load F is normalized by the critical value F_{cr}. It is found the loosening rotations of the SW joint are larger than that of the standard joint. The rate increases drastically around $F/F_{cr} = 0.80$ ($F = 1200$ N) in the case of the SW joint. The value of 1200 N corresponds to the shifting point from stage B to C in Fig. 8a. Therefore, it is supposed that the increase in loosening rate is caused by the rotation around the two stuck edge points, as described in Fig. 9.

4. Discussion

4.1. Comparison to the experimental results of SW joint by Sakai

Sakai performed loosening tests using Junker's loosening apparatus that leads to large transverse displacement of a cramped plate [3]. Results of FE analyses that model their experimental setups are compared to experimental ones in this chapter.

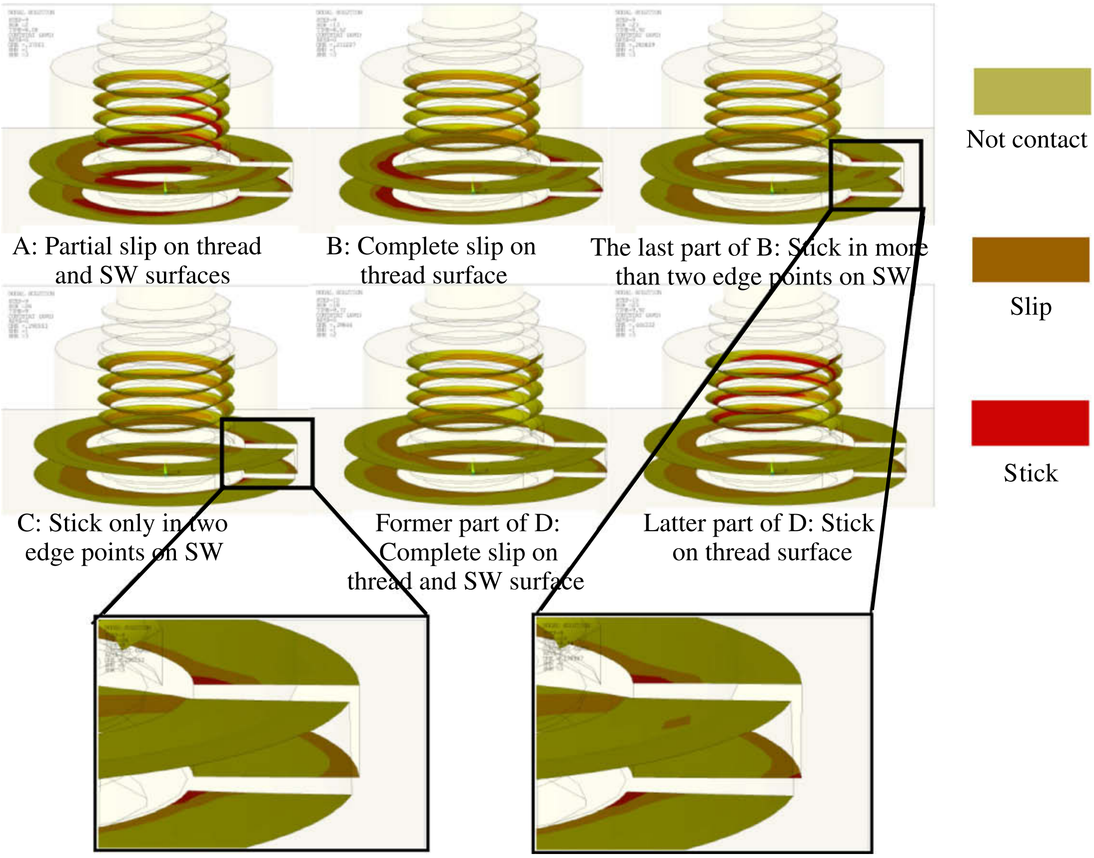

Fig. 9. Classification in contact states.

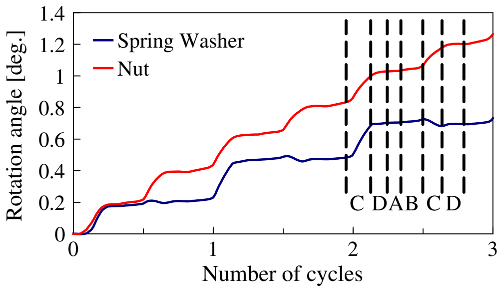

Fig. 10. Loosening rotation angle of the spring washer.

Analysis conditions are described below. A fine M10 bolt with 1.25 mm pitch is employed with a nut and a SW, and the grip length is set to 32 mm. The total amplitude of the transverse displacement applied to the movable plate is set to 1.0 mm in order to adjust with the experiment. Thread and bearing surfaces were lubricated with machine oil, while the friction coefficient of the contact surfaces is set to 0.125 in the analysis. More than 1000 vibration cycles were performed in the experiment. However, it is not realistic in this analysis method due to computational costs. Therefore, it is decided to perform loosening analyses for three vibration cycles under the conditions of several kinds of bolt tension (5–30 kN) and observe the decrease rate of bolt tension (decrease in bolt tension per cycle).

The decrease rates of bolt tension are shown in Fig. 14. The decreases in bolt tension during third cycle are plotted. Loosening due to micro bearing-surface slip occurs at the bolt tension of 30 kN in the standard joint while it occurs at 20 and 30 kN in the SW joint. Loosening due to complete bearing-surface slip occurs in the cases less than those values. It is shown that the decrease rate is almost proportional to the bolt tension under the condition of complete bearing-surface slip.

The decreases in bolt tension by the loosening due to complete bearing-surface slip are shown in Fig. 15. FE curves are derived from the least-squares approximation line of the plotted decrease rate in Fig. 14. FE curves are shown over 5 kN that

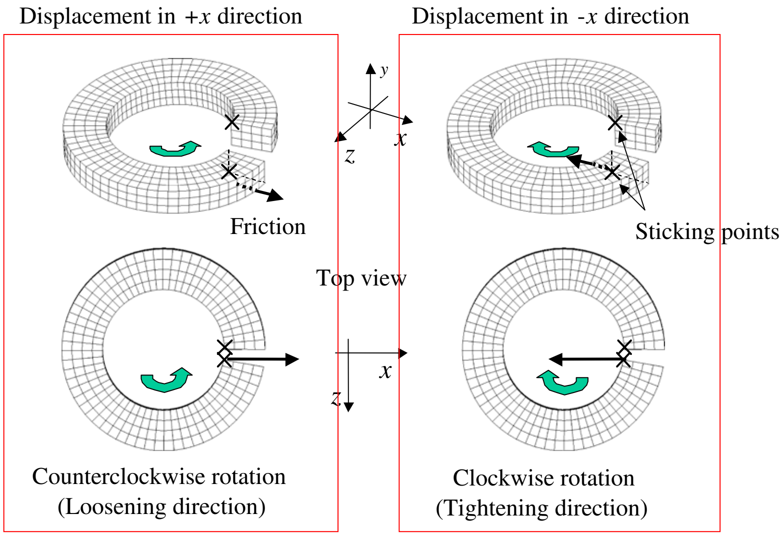

Fig. 11. Schematic illustrations of washer rotation during C state.

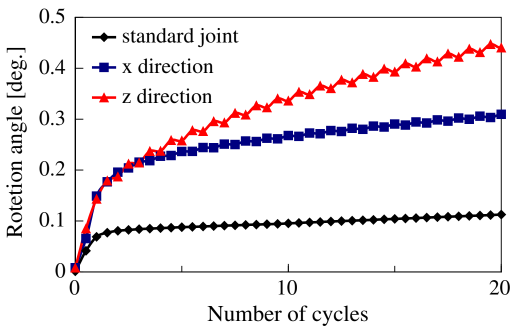

Fig. 12. Loosening rotation angle under 1000 N loading.

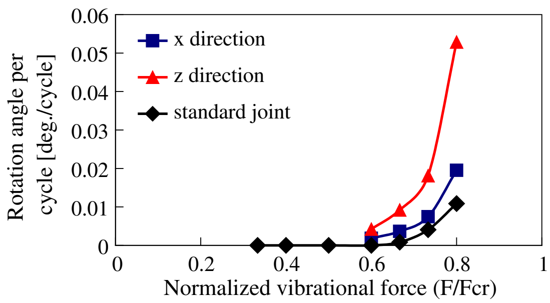

Fig. 13. Dependences of loosening rate on normalized vibration force.

is the minimum bolt tension analyzed in this examination. The FE results agree qualitatively with experimental results in that the decrease in bolt tension is slower as the bolt tension is smaller. However, the decrease progresses faster in the FE analyses than in the experiments. The reason might lie in the difference in coefficient of friction and boundary conditions between the experiment and the analysis, some gradual change in contact surface condition in the experiment, and so on.

The experimental results show that the decrease in bolt tension becomes slower in the SW joint than that in the standard joint as the bolt tension becomes smaller. However, some experiments, including Yamamoto and Kasei [1–2], showed contradicted results. It is considered that the loosening-resistance mechanism of SW has not been discussed enough from the experimental results. Therefore, any conclusion is not reached on the effect of SW. On the other hand, the FE results do not show the tendency that the decrease in bolt tension becomes slower in the SW joint as the bolt tension becomes smaller. The

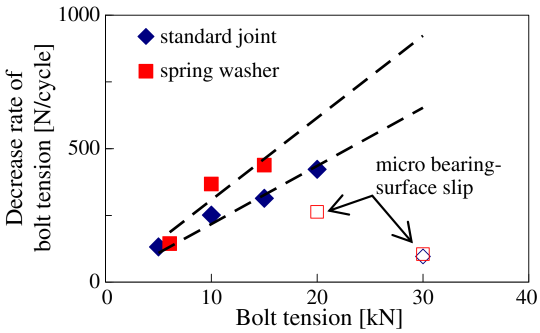

Fig. 14. Decreasing rate of bolt tension.

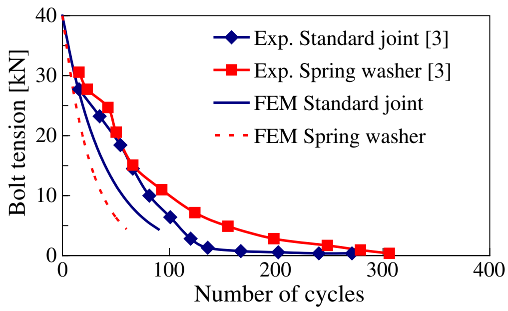

Fig. 15. Comparison of decrease in bolt tension between FE and experimental results.

loosening analyses became unstable under the bolt tension of 5 kN and valid results were not able to be obtained in that region. However, it is expected that the analysis results in this study help us to understand the mechanism of SW and establish some guideline for employing it.

4.2. Application of DN and SW

On the basis of the results shown above, we discuss the application of loosening-resistance components. It is clear that DN has a good loosening-resistance performance. Even if the transverse load enough to cause complete bearing-surface slip is applied, loosening would be drastically suppressed by DN. However, in actual tightening operation, the problem is a reliable control of locking state. To set up the locking state is not easy because serious control of the tightening torque is necessary in three tightening processes; tightening of the lower nut, tightening of the upper nut, and rotating of the lower nut in the loosening direction.

On the contrary, such a troublesome problem does not take place in SW tightening. However, as compared with DN, SW is not able to suppress loosening due to both bearing and thread surface slip. It should be noted that the SW induces significant loosening rotation prior to the bearing-surface slip. Although SW shows some effect in the experiment that the bolt tension is retained under the low bolt tension, we suggest that SW should not be used as a loosening-resistance component without sufficient discussion. On the other hand, we observed that conical spring washer (CSW) provides a certain effect on loosening resistance since it gives a higher spring force than SW, and the force contributes to retain the bolt tension during loosening rotation of nut [14]. Therefore, it is expected that CSW shows better loosening-resistance performance than SW.

5. Conclusion

Three-dimensional finite element analyses of M10 bolted joints using double-nut tightening method (DN) and a spring washer (SW) subjected to a transverse load were performed and the loosening-resistance performances of those components were investigated.

First, in regard to DN, the effect of the locking state on preventing loosening was clarified. We have found that if locking state is properly achieved in its tightening process, DN shows significant loosening resistance. The magnitude of locking force affects the variation in bolt tension during vibration. The variation is smaller as the locking force is larger. The transverse load–displacement relation consists of a slope and a flat region in the locking state, while it consists of two kinds of slopes and a flat region if locking state is not achieved. The contour plot of the contact states showed that the effect on preventing loosening is caused by the mechanism that the upper nut thread retains stuck state even if the nut bearing-surface undergoes complete slip.

Secondly, it was shown that SW enhances loosening rotation of nut. The stuck region on the contact surfaces is reduced to two corner edges of the SW and the rotational force around these edges thus drastically leads to loosening before complete bearing-surface slip. This variation in contact states adds an extremely gradual slope to the transverse load–displacement relation. SW joint loosens faster than standard joint as the applied load approaches the critical value of complete bearing-surface slip. SW is considered to be ineffective from the viewpoint of loosening resistance.

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