Self-loosening of Nuts due to External Load

Yasumasa Shoji,
Chiyoda Advanced Solutions Corporation,
Yokohama, Japan,
Yasumasa.shoji@chas.chiyoda.co.jp,

Toshiyuki Sawa
Hiroshima University
Hiroshima, Japan
sawa@mec.hiroshima-u.ac.jp

Abstract: Self-loosening of nuts is a practical problem in any situations from a machine to a whole plant. Self-loosening of threaded bolt/nut systems has been researched in number of works and many of them were based on experiment historically and some were based on the finite element analyses in these years. In this paper the following self-loosening were investigated by Abaqus, namely the static loosening of nut due to the lateral motion, dynamic loosening due to the lateral impact of fastened objects and the thermal load to bolt/nut systems. In the static lateral motion, the fastened plate is subjected to the lateral motion and the loosening is reproduced. This is the situation of so-called Junker's test. The Dynamic model is the reproduction of NAS 3350 test. In the thermal load case the bolt and nut are subjected to temperature difference between each other. Self loosening phenomenon is discussed in the unified manner, and the countermeasures are addressed in this topic.

Keywords: Bolt, Nut, Self-loosening, Mechanism

1. Introduction

It is well known that bolted joints are loosened when lateral loads are applied to the joint after they are tightened. The lateral loads may be static or dynamic. This self-loosening of the bolt is observed in any bolted joints, which results in risks of failure for any machinery or equipment. The most practical countermeasure of the bolt loosening so far is periodic re-tightening of them to keep the required or desired bolt tension. This is known as "hot bolting". As this re-tightening requires the periodic maintenance of the machinery, and as there are usually a large number of bolts at one plant site, the maintenance cost becomes significantly large in most cases.
Besides the cost, this type of maintenance is strongly required to be eliminated or, at least, to be reduced as much as possible, because it has a big risk of another failure. It is because failure often occurs at the plant shut-down and start-up and this maintenance work does not create any benefits. Thus, if we can reduce or eliminate the bolt loosening, it will be very beneficial to the industry, as it prevents the loss due to the maintenance and the loss of possible benefit during the plant stops. As these losses are neither economical nor ecological, eliminating the retightening may be beneficial to the society, too.
There are some researches (Zhang, 2004(1), 2004(2)), (Yamamoto, 1984), (Sakai, 1978) which investigated the bolt loosening phenomenon, but the mechanism of the loosening is still unclear and the general countermeasures for the loosening are not achieved. Some researches are based on Finite Element Analyses these years (Sakai, 2005), (Zhang, 2004), (Shoji, 2005, 07, 08, 09).

In this paper, investigation of the self-loosening in (quasi-)static and dynamic (impacting) conditions were carried out as well as under thermal condition. Authors show experimental results using Junker's loosening test (Junker, 1969), and NAS3350/3354 ("NAS test" in the following sentences)(NAS, 1992) loosening test were also addressed.
In these simulations, the nut rotation was reproduced and the principle of loosening is discussed in all the load conditions.

2. Analytical Methods and Analytical Models

The following 3 load conditions were investigated for the self-loosening.
(1) Nut loosening when the fastened plate is subjected to prescribed motion. In this case, the bolt deformation is so small that the bolt shank does not touch to the bolt hole. == Case "Static Lateral Motion".
(2) Nut loosening when the fastened part and the bolt/nut impact to the wall. In this case the inertia of the nut is the major lateral load to the self-loosening as represented by NAS3350 test. == Case "Dynamic Impact".
(3) Nut loosening when the bolt and nut are subjected to cyclic thermal loads. This case also treats the changing of the bolt pretension. == Case "Thermal Cyclic Loading".

2.1 Static Lateral Motion Model

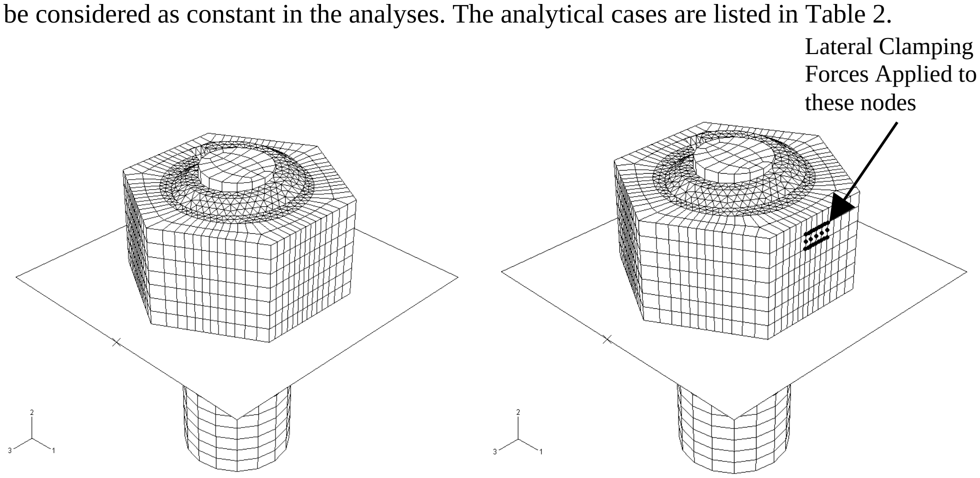
Figure 1 shows the analytical models. Figure 1(a) is the hexagon nut, and Fig. 1(b) is the eccentric nut. Each model consists of a nut, a bolt and a plate. The bolt and the nut are modeled as deformable bodies and the plate is assumed as a rigid body for simplicity. The plate does not have a hole for bolt, but it does not lose generality, as the prescribed displacement of the plate is 0.1mm which is small enough not to lead bolt contact to the bolt hole. The magnitude of plate motion for analyses is smaller than that of the experiment using Junker's test machine. Friction is considered between the surfaces of bolt and nut threads and between the nut and the plate. The frictional coefficients are 0.1 for both contact surface pairs.

In the analytical model, "pre-tension" capability (Abaqus, 2009) was used to apply the pretension to the bolt, and to "fix the current length" in the subsequent steps. The prescribed motion of the plate and wedging lateral force of the eccentric nut are applied in this "fixed" condition.
Materials used in this model are listed in Table 1. The bolt and the nut are basically linear elastic.

The followings are the explanations of the individual nut model:
(a) Normal nut:

The configuration of M12x1.75 (JIS, 2009) was used. The length of the bolt was 30mm. As design tolerance was taken into account, small gap (0.032mm) between the threads was considered; only one side of thread surfaces contacted each other. The generality of the loosening results will not be affected by the bolt size. The model is shown in Fig. 1.
(b) Eccentric nut:

According to the concept of the brochure (Hard Lock, 2004), the principle of this nut is to utilize the wedging effect by continuously applied lateral clamping force to the nut preventing loosening. For the real bolt, this lateral clamping force is achieved by the combination of the eccentrically tapered base nut and the top nut. In this analysis, this effect is represented by only the lateral force applied to the normal nut without modeling the tapered surface nor the top nut. The lateral force is applied as nodal forces to the nodes indicated in Fig. 3(b). The force is normal to the bolt axis, thus the direction is in –X. Although the nut rotation occurs and the force direction may change accordingly, but the magnitude of the angle is negligibly small and the direction can be considered as constant in the analyses. The analytical cases are listed in Table 2.



(a) Analytical Model of Normal Nut **(b) Analytical Model of Eccentric Nut**

Figure 1. Analytical model of Static Analyses.

Table 1. Material Properties.

Young's modulus	200000MPa
Poisson's ratio	0.3
Yield stress	250MPs
Density	7.8E-9 kg/mm3
Thermal Expansion	1E-5 1/deg C

Table 2. Static Analytical Cases.

	Nut Type	Pretension[N]	Friction Coeff	Lateral Clamp[N]	Denotation
1	Normal	1000	0.1	--	N_1000
2	Normal	8000	0.1	--	N_8000
3	Eccentric	1000	0.1	460	E_1000_460
4	Eccentric	8000	0.1	460	E_8000_460
5	Eccentric	8000	0.1	3680	E_8000_3680

2.2 Dynamic Impact Model

This section treats dynamic state, while all analyses and phenomena were based on static conditions in the previous section. The previous section addressed the conditions of transverse vibration of fastened joints, but the vibration velocity is rather slow as Junker loosening test machine so that we can consider them as (quasi-)static condition. In this section a dynamic condition is considered in which the inertia of the nut is the major transverse load to the self-loosening as represented by NAS3350 test (NAS test hereafter).

NAS test is the self-loosening test in which the bolted cylinder is shaken with impacts. In this test, the self-loosening of the nut is observed by these impacts. The transverse load is solely determined by the inertia due to the nut mass and the acceleration at impact. As the loading mechanism is completely different from the previous section, we need to carefully observe and compare the results.

The analytical model is based on the mechanism of NAS test and the model configuration will be described later in the following sections. The test configuration is shown in Fig. 2. The plate with the slots vibrates up and down. When the plate moves and returns, the cylinder impacts to the end of the slot and the impact load is applied to the nut. This up/down motion is repeated 30000 times with the frequency of 1800rpm (30Hz), and the loosening of the nut is examined. As this model includes impacts, Abaqus/Explicit was used for the analyses. Although the real length of the slit is 44.323 mm for 1/2 inch bolt and the frequency is 30Hz, the analytical model employed 30 mm of the slit length and 300Hz of frequency accommodating 4mm gap between the cylinder and the slit, as the real condition takes too long for the explicit analysis. This modified condition enables the shortening of the computational time without loosening generality regarding the determination of transverse load by impacts.

The material is assumed as elastic, and the bolt properties from Table 1 are used.

The analytical model for the dynamic analyses is shown in Fig. 3. Figure 3(a) is the whole configuration with the surrounding rounded wall represents the slit of NAS test plate. This wall is modeled as a rigid body. Figure 3(b) is the bolt and nut model without showing the surrounding wall. Figure 3(c) shows the portion that is thermally shrunk to achieve bolt tension, as Abaqus/Explicit does not have “bolt-tension” capability. Initially the cylinder is located at the center of the slot without contacting to the wall. The prescribed sinusoidal motion was applied to the wall in the direction of the longitudinal axis of the wall. Other than the normal nut, eccentric nut was considered. To model the eccentric nut simply, the lateral force was applied to the normal nut, which is the main effect of eccentric nut.

The following design parameters were considered:

(a) Pretension of each bolt: 8000N and 16000N (8000N is 1/3 of yield strength.)
(b) Friction Coefficient: 0.1 and 0.2
(c) Lateral Force of Eccentric nut: 10KN and 50KN

The combinations of these parameters are shown in Table 3.

The analysis consists of 2 steps: the bolt pre-tension is applied to the bolt in the first step, and the dynamic prescribed motion is applied to the rigid wall in the second step. The frequency of the wall motion is 300Hz and the motion length is 20mm. The duration of 3 cycles of vibration was calculated.

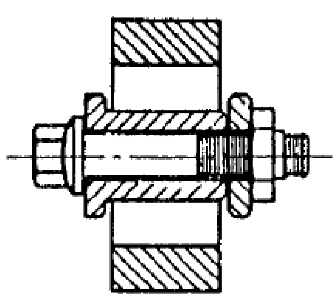
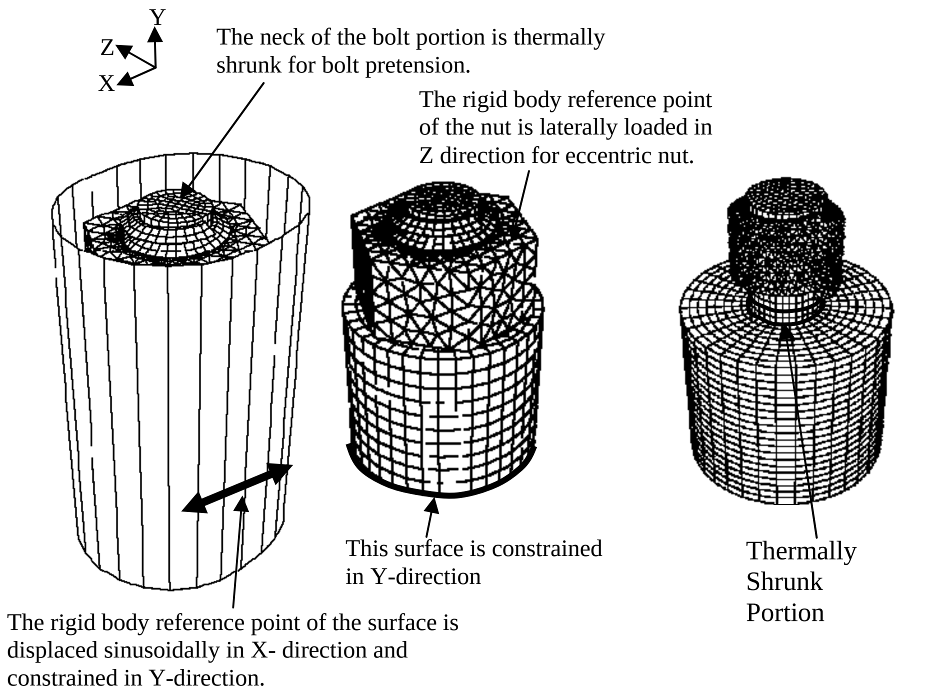


Figure 2. NAS3350 Test Configuration.

Table 3. Dynamic Analytical Cases.

No	Nut Type	Tension [N]	Fric-tion	Transverse Force [N]
1	Normal	8000	0.1	
2	Normal	8000	0.2	
3	Normal	16000	0.1	
4	Normal	16000	0.2	
5	Eccentric	8000	0.1	10000
6	Eccentric	8000	0.1	50000
7	Eccentric	8000	0.2	10000
8	Eccentric	16000	0.2	50000



(a) Whole Configuration **(b) Bolt/Nut Portion** **(c) Bolt Tension Model**

Figure 3. Analytical model of Dynamic Analyses.

2.3 Thermally Cyclic Loading Model

Fig. 4 shows the analytical model. This analytical model is basically the same model as used in the static analysis.

The bottom end of the bolt was fixed as the boundary condition. The fastened plate modeled by the rigid surface was fixed in the space in this section, while it was subjected to prescribed displacement in the previous section. Three types of loads were applied to the bolt or nut directly. The loads are thermal load to the bolt, tensional load to the bolt and thermal load to the nut. The model axes are shown in Fig. 4 and these directions are important in evaluation of the results. To apply bolt tension, the bolt-pretension capability of Abaqus was used. This capability can handle the change of tension load due to thermal loads. In the analysis the first step was the pre-tension step and the thermal loads were applied in the following steps. These steps are displayed in the time history results and the rotation due to thermal loads starts from the second step.

The thermal load to the bolt changes the length of the bolt by thermal expansion and it also changes the radius of the bolt (or nut). Thus the length change and/or radius change may cause the self-loosening, when the nut becomes loose due to the thermal load to the bolt. The length change

causes the tension change. In order to investigate the effect of the tension change, the changing tension to the bolt was directly applied. In the same way, the radius change was examined by applying thermal load to the nut, in which the tension is not change very much as the bolt length is fixed. As the heat sauce of the flange is normally the internal fluid and the heat path is fluid → flange → nut → bolt, nut and bolt have the different temperature. In case of cooling, the path is opposite direction. In this paper, the uniform temperature change was used in the whole bolt or the whole nut mainly for simplicity, but it will not lose the generality of the phenomena.
The analytical cases in Table 4 were considered. The meaning of each case will be discussed in the following sections. The initial temperature of the models was assumed as 0 degree and the temperature changes from zero in all the cases, as thermal expansion is considered all "relative".

The material properties in the analyses are taken from Table 1. The friction is set to 0.1 for all contact surfaces. If the friction coefficient is different, the behavior may differ, however, it will be the future work.

Table 4. Thermal Analytical Cases.

Pretension	Bolt Temp [C]	Nut Temp [C]	Tension Range
1000	-50		
1000	50		
1000		-50	
1000		50	
1000			500-1500
8000	-50		
8000	25		
8000	50		
8000	70		
8000			100-8000
8000			4000-12000
16000	50		

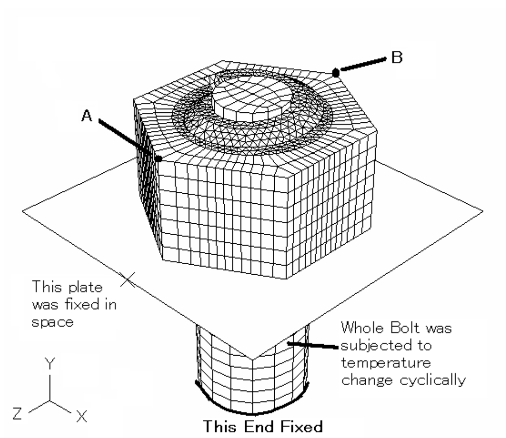


Figure 4. Thermal Analytical Model.

3. Analytical Results

Analytical results are addressed below. In the static analysis, some experimental data are also introduced.

3.1 Static Lateral Motion Model

The results for M12 are described in the following sections. To verify the analytical results, loosening test by Junker Test Machine described as well.

Experimental Method

The effect of some parts and nuts for preventing the screw thread self loosening such as plain washer, spring washer, double nut, eccentric nut, nylon inserted nut, slit nut and so on was evaluated using Junker's type loosening machine. Figure 5 shows the schematic of Junker's type loosening machine used in the experiments. This machine was fabricated according to the reference (Junker, 1969). The nominal size of bolt and nut is M10×1.5. In the tests, the bolt preload is chosen as 12.5 kN. These bolt preloads correspond to 70% of the bolt yield stress. The bolted joints was tightened with the preload and in the loosening tests, the transverse displacement S was chosen as 0.35mm and the maximum numbers of the transverse repeated displacement was chosen as 500.

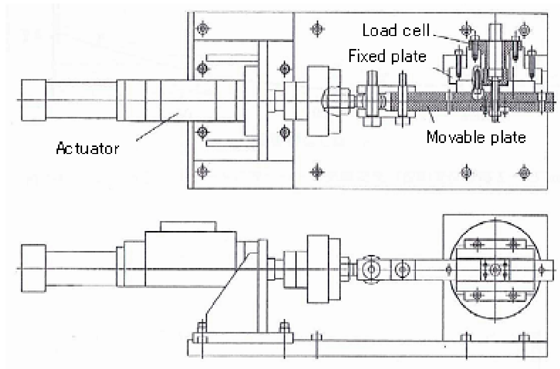


Figure 5. Junker's Loosening Test Setup.

Experimental Results

Figure 6 shows the results in the loosening tests. The bolt load was lost completely in most cases and in other several cases, bolt load still remained. In the cases of the eccentric nut, the reduction in bolt load was small. In all the cases, bolt load reduction is faster at the earlier stage and it indicates that bolt loads are easier to loose when it is larger.

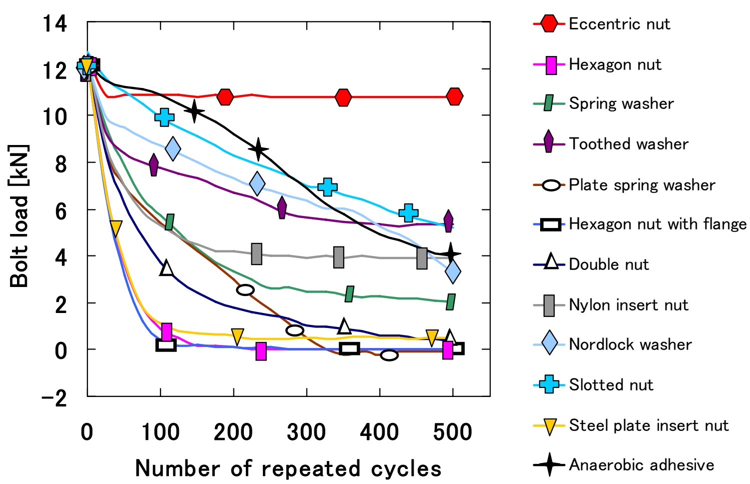


Figure 6. Junker's Loosening Test Result. (Tension 12.5kN)

Analytical Results

(1) Rotational Angle

Figure 7 shows the result of the rotational angle of the nuts. The normal nuts (denoted as N_1000 and N_8000) are loosened, and as pre-tension increases, the rotational angles are larger. These phenomena agree to the test, as the slope of rotational angle to cycle number is steeper when the bolt tension is larger. The eccentric nuts do not show loosening when they are sufficiently loaded in the lateral direction due to the tightening of the second nut (E_8000_3680). However, they become loose when the tightening of the second nut is not sufficient (E_8000_460). The tension is this source of the lateral force of the plate.

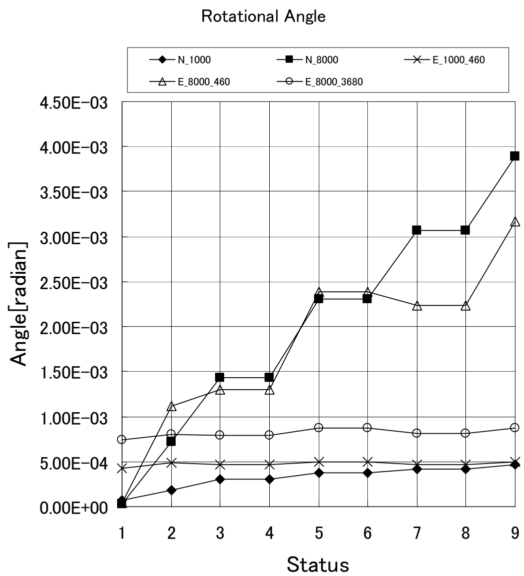


Figure 7. Rotation Time History in Static Analysis.

(2) Bolt Tension Change

Figure 8 shows the result of the changing of the bolt tension. The tendency is identical to the rotational angle. The normal nut loses its tension as the nut rotates, and the eccentric nut does not lose its tension when the second nut is tightened sufficiently. In the same figure, the tension of the eccentric nut occasionally increases. This is because that the applied lateral force enforces the nut thread to slide on the bolt thread surface, which causes the extension of the bolt in a small amount.

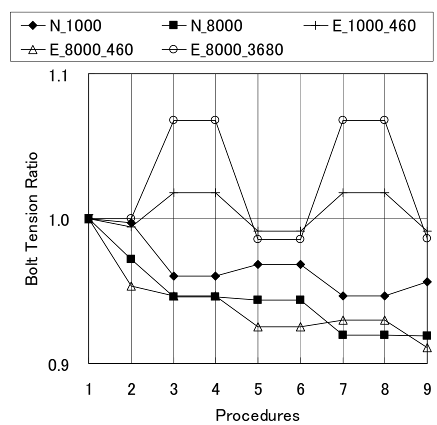
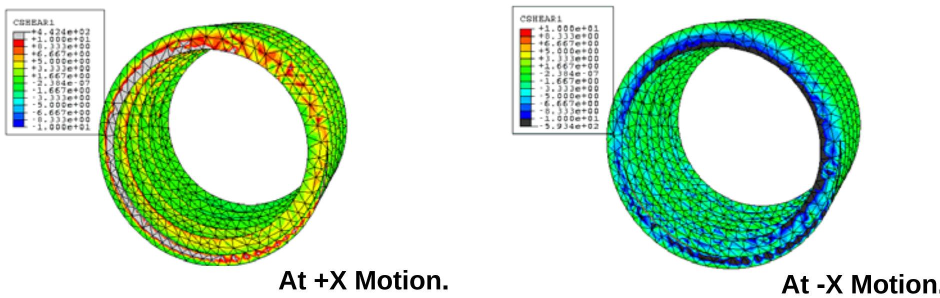


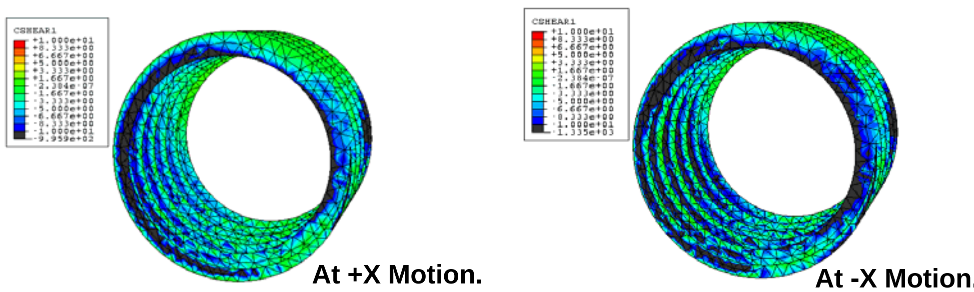
Figure 8. Tension History.

Figure 9 shoes the sear stress between the threads of the bolt and nut. Figure 9(a) is the result of loosening normal nut and Fig. 9(b) is the result of eccentric nut which was not loosened.

In these cases, nut rotation, which results in nut loosening, is observed when the shear friction is alternating. This phenomenon is common for all the loosening cases. On the contrary, if some portion of the thread surface keeps the shear friction not alternating, the nut loosening becomes smaller or negligible. This condition can be achieved using special nuts such as eccentric nuts and so on. It is obvious that self-loosening occurs due to the relative rotation between bolt and nut thread surfaces, and this rotation is caused by the relative slip between the surfaces. This relative slip is considered to occur due to the alternating shear stresses on the thread surfaces.



(a). Cshear1 of Normal Nut (Loosened Case) Tension 8000kN.



(b). Cshear1 of Eccentric Nut (Unloosened Case) Tension 8000kN.

Figure 9. Shear Stress Distribution in Static Analysis.

3.2 Dynamic Impact Model

The analytical result of nut rotation is shown in Fig. 10 and Fig. 11. Fig. 10 is the nut rotation of the normal nut with the tension of 8000N, indicated as No.1 in Table 3. Fig. 11 shows that nuts are less loosened if the lateral forcing is larger. It is the case where the inertia plays the major role of transverse load for self-loosening at impacts. It also shows that in such conditions, the larger frictional coefficient between thread surfaces and that between nut surface and the bearing surface of fastened object plays another role to reduce the loosening. It is also observed that the nut with sufficient lateral force loosens less, even if the nut is the same as normal nut. This lateral force can be introduced by an eccentric nut in the practical machinery. Among all the cases, the frictional meridialnal nodal forces are shown in Fig. 12 and Fig. 13 for the most loosened nut (No.1 of Table 3) and the least loosened nut (No.8 of Table 3), respectively. Figure 12 and 13 shows the meridional frictional nodal forces at the impact conditions in the -Z direction and in the +Z direction. The meridional shear forces alternates at impacts for loosening nut, but it does not alternate too much for least loosening the normal nut. As seen in Fig. 13, the frictional force changes but some amount of shear is maintained in the same direction. This is the same observation as in the static analyses. This means that the mechanism of loosening is identical for every nut which is subject to the transverse load to the fastened plates. The countermeasures are considered also the same as static.

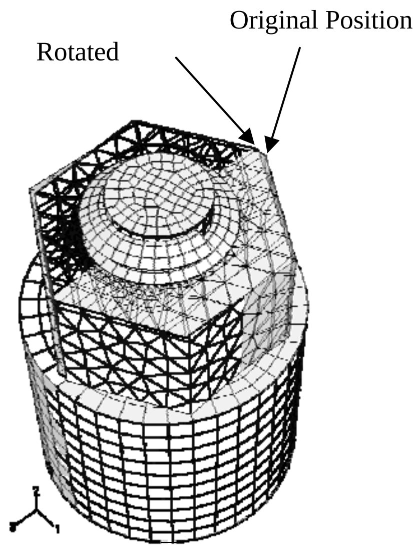


Figure 10. Dynamically Deformed Shape.

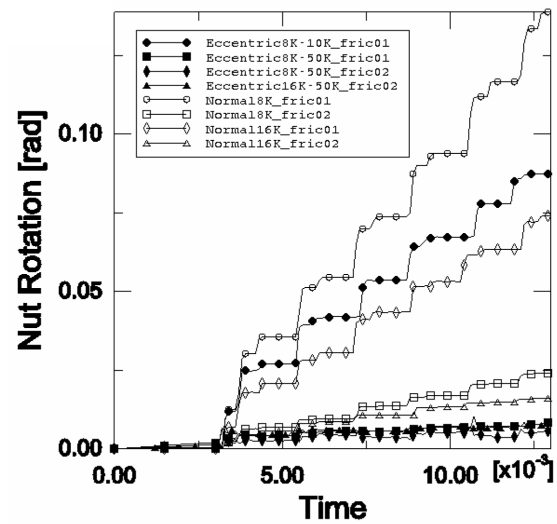
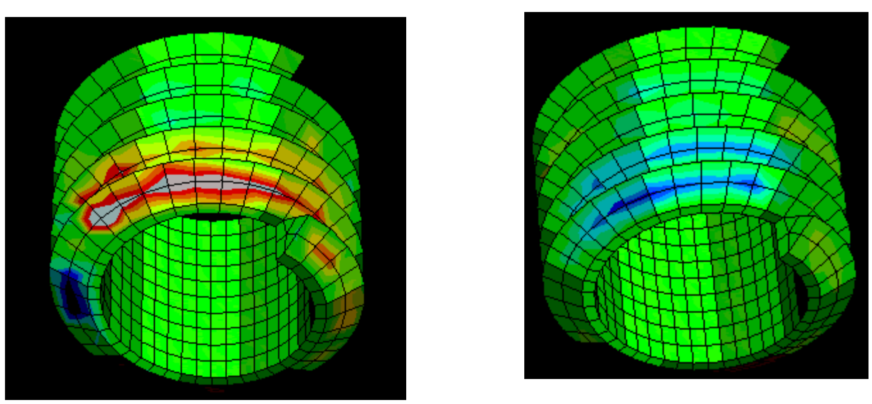
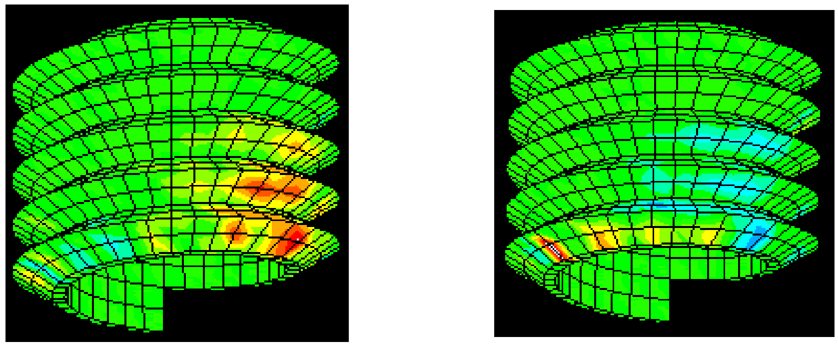


Figure 11. Dynamic Nut Rotaion Time History.



Just after +X impact. **Just after -Z impact.**

Figure. 12. Cshear of Normal Nut (Loosened Case) Tension 8000kN.



Just after +Z impact. **Just after -Z impact.**

Figure. 13. Cshear of Eccentric Nut (Unloosened Case) Tension 16000kN.

3.3 Thermally Cyclic Loading Model

In the previous sections, the nut was subjected to the lateral alternating loads, and it was observed that the self-loosening may occur when the frictional shear between the thread surfaces alternates. When bolt and nut are subjected to different temperature, the thread surfaces slide against each other, and may occur alternating of shear stress. This may lead the nut loosening (and it is observed in the real plants.)

As noted in the "Analytical Model" section, there are 3 types of analyses: (1) Bolt was heated or cooled including tension changes and slip in the thread surfaces, (2) only tension was changed, and (3) nut was cooled or heated which realizes the slip between the thread surfaces.

Self-loosening due to thermal load to the bolt

Three pretension conditions, 1000N, 8000N and 16000N, were selected for this type of analyses. 1000N represents very low clamping force, 8000N corresponds to the clamping force based on the one third of the yield stress, and 16000N is the high tension which is double of standard tension with 2/3 of yield stress.

The thermal load is basically the thermal cycles in which the temperature change to the certain point (heated or cooled) and it returns to the original point. This temperature cycle is applied several times to the bolt.

In the case of 1000N tension, cooling of -50 degrees C and heating of 50 degrees C was considered. In the 8000N cases, cooling of -50 degrees C and heating of 25, 50 and 70 degrees C were examined. Only heating of 50 degree C was considered in 16000N case. The analytical results of nut rotation are shown in Fig. 14, with changing bolt temperature. It shows that loosened cases are -50 degree C of 1000N, 50 and 70 degree C of 8000N and 50 degrees C of 16000N. The case of -50 degree C of 8000N was also loosened, but the amount was small. In the case of 50 degrees C of 1000N, bolt tension was completely lost due to the bolt thermal expansion, and the calculation aborted. The relationship between tension and the rotation angle is summarized in Fig. 15 for 8000N tension cases.

These phenomena explain that larger temperature amplitude causes loosening, and the lower tension is easier to be loosened.

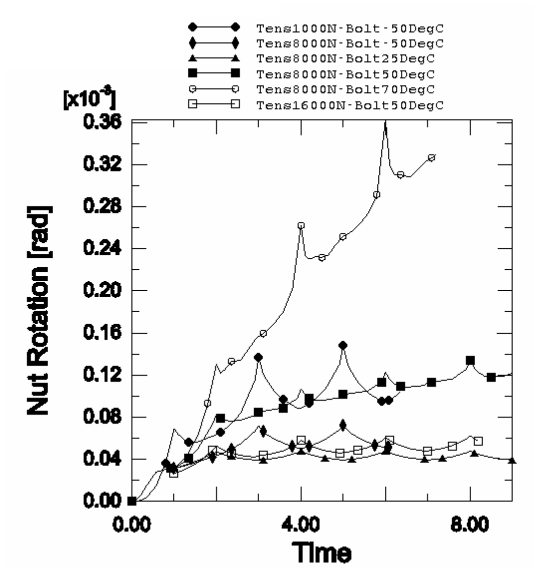


Figure 14. Time History of Nut Rotation for Bolt Temperature.

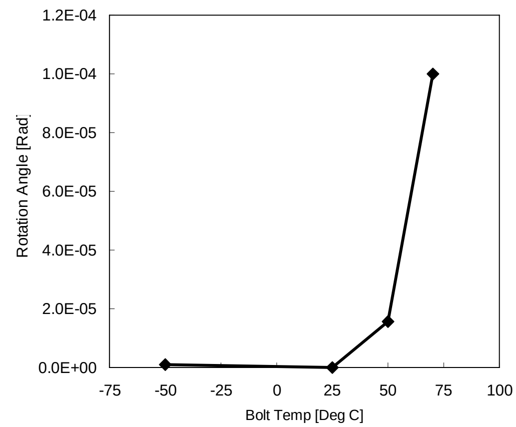


Figure 15. Relationship between Nut Rotation and Bolt Temperature changes for 8000N tension.

Self-loosening due to tension changes to the bolt

Bolt loosening due to temperature change is considered to be caused by the tension change due to the bolt thermal expansion or radial slip between thread surfaces.

In this section the tension change is applied to the bolt without changing temperature. In this series of analyses, three cases were tried. The first one has the 8000N pretension and the tension changes to 100N and return to 8000N, the second one is pre-tensioned to 8000N and the clamping force and it changes from 4000N to 12000N and the last one has 1000N pretension and the tension changes between 500N and 1500N. The analytical results are shown in Fig. 16. In this figure, the first pre-tensioning was omitted and the plots start from step 2 which is the beginning of the tension changes. As the results, the rotation is small when only tension was changed.

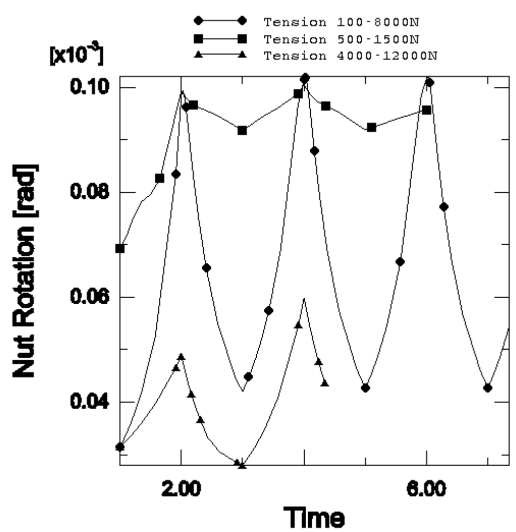


Figure 16. Time History of Nut Rotation by Bolt Tension.

Thus the bolt length change due to thermal load does not play a major role of self-loosening.

Bolt tension changes in practical situations usually when axial load is applied to the bolted flange. The load can be a mechanical force from piping system or thrust end force due to internal pressure.

Self-loosening due to thermal load to the nut

The thermal loads to the nut with 1000N pretension bolts were examined. As described before, this is the case to consider the relative motion between thread surfaces, with eliminating the bolt tension change. The nut is subject to cooling of -50 degrees C and heating of 50 degrees C. The cooling of -50 degrees to the nut corresponds to the heating of 50 degrees to the bolt, and contrary is the case. The results are shown in Fig.17. When the nut is heated, the self-loosening occurs, while the nut is not loosened when it is cooled. This difference is caused by the unsymmetrical condition between the thread surfaces.

From all of the results, it is estimated that the self-loosening of the nut due to thermal load is not caused directly from the tension change, but the relative motion of the bolt and nut relates to the large loosening.

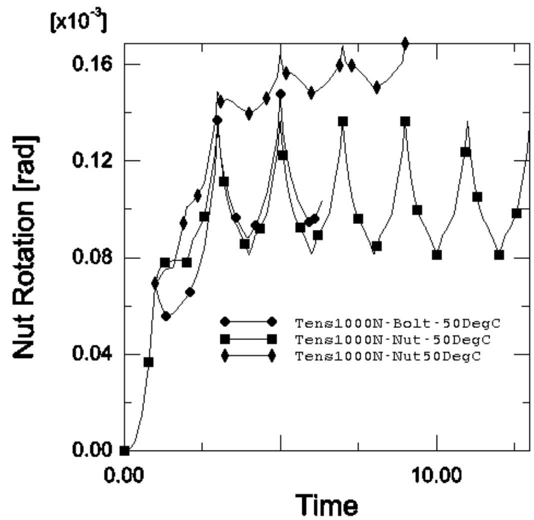


Figure 17. Time History of Nut Rotation for Nut Temperature changes.

4. Discussion

Static – plate motion –

In the cases where the nut is self-loosened due to the lateral loads, shear strain occurs on the contact surfaces of the threads. As the bolt is pre-tensioned, the thread surfaces contact only on one side. The shear strains are almost the same in the fore and aft position of the bolt thread in the directions of plate motion, and they cause the same slip along the plate motion direction. In this situation, as the screw has the helical shape, the slip in the plate motion direction becomes the symmetric slip in the transverse direction. The opposite transverse slip directions corresponds to the same rotational direction around the bolt axis. This is the basic principle of nut rotation. Although the slip or shear deformation are very small for one cycle, but the lateral loads are applied in a large number of cycles, and the accumulated slip will cause loosening. In this discussion, it is essential that the slip along the plate motion should alternate with the plate displacement. If the slip is recovered and the relative position change of the thread surfaces is very small or none, the loosening will not occur. Thus, if we can prevent the alternating shear stress, it will be a good countermeasure for self-loosening. The essence is to keep the frictional force constant between the bolt thread and the nut thread. The eccentric nut intends to do it by lateral force by the combination of eccentrically tapered base nut and the top nut, and it succeeds to prevent loosening,

When we see the results of shear stress on the thread surfaces, the nuts which were loosened show the alternating shear stress, while the non-loosened nuts do not.

This concludes that we need to apply any loads to prevent alternating shear stresses. These loads will help to prevent bolt loosening

Dynamic

The discussion for the static load is also true for dynamic load. In order to prevent or decrease bolt self-loosening, the following types of means are normally used:

(a) to increase pre-tension,

(b) to utilize special types of nuts.

Increasing the pre-tension works for dynamic condition but the effect is rather limited. This measure only lengthens the time to lose bolt tension. Special type of nut, namely eccentric nut, works well by adding the fixed lateral force to keep shear condition. In this dynamic case, the alternating shear stress makes the main role to cause self-loosening.

Thermal

This thermal load case is the one way load, high or low temperature, which does not alternate. Bolt tension load change is also one way, as tension is always tension and does not become compression. These are not expected to alternate in principle, but the loosening occurs in some cases. The shear friction between the thread surfaces are observed for the cases where the loosening occurs or does not occurs.

It is observed the shear alternates and no portion keeps the same shear in the cases where self-loosening occurs. The shear is in one direction, but the distribution is not collocated in its direction and it offset to the transverse-direction. This means that shear stress in circumferential direction is included, and may cause the rotational torque to loosen the nut. Radial shear occurs within the same sign, plus or minus, but it causes alternating circumferential shear. It may be the main cause of self-loosening, as the previous sections considered.

These phenomena agree very much to other loadings.

5. Conclusions

As the result of the analyses and the discussion, the following conclusions were obtained:

(a) There are many types of nuts and most of them are self-loosened. Some types of nuts are more difficult to become loose when lateral loads are applied.

(b) The mechanism of the loosening is caused by the alternating frictional (or shear) stress between the thread surfaces, in both static and dynamic conditions.

(c) To reduce the loosening, it is important to keep the frictional stress constant by preventing the stress alternating.

(d) Self-loosening may occur when temperature differs between bolt and nut, and the temperature changed cyclically.
(e) Tension change may not affect nut loosening very much.
(f) Relative motion between bolt and nut, especially in radial direction, has a large effect in the self-loosening by generating alternating shear stress.

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7. References

1. Zhang M. and Jiang Y., 2004, "Finite Element Modeling of Self-Loosening of Bolted Joints," Proceedings of PVP2004 Vol. 478, pp.19-27
2. Zhang M. and Jiang Y., 2004, "An Experimental Investigation of the Effects of Clamped Length and Loading Direction of Self-Loosening of Bolted Joints," Proceedings of PVP2004 Vol. 478, pp.129-136
3. Yamamoto A. and Kasei S., 1984, "A Solution for Self-Loosening Mechanism of Threaded Fasteners Under Transverse Vibration," Bull, Jpn. Soc. of précis. Eng., 18, pp.261-266
4. Sakai T.,1978, "Investigations of Bolt Loosening Mechanisms : 1st Report, On the Bolts of Transversely Loaded Joints," Bulletin of JSME, Vol21, pp.1385-1390
5. Sakai S. 2005, "Three-dimensional Finite Element Analysis on Tightening and Loosening Mechanism of Bolted Joints," Engineering Failure Analysis, 12-4, pp. 604-615
6. Zhang M. and Jiang T.,2004, "Finite Element Modeling of Self-Loosening of Bolted Joints," Proceedings of PVP2004, Vol.478, pp.19-27
7. Shoji Y. "Analytical Research on Mechanism of Bolt Loosening due to Lateral Loads," Proceedings of PVP 2005, PVP2005-71333 (CD-R)
8. Shoji Y, Sawa T. and Yamanaka H. "Self-loosening mechanism of nuts due to lateral motion of fastened plate," Proceedings of PVP 2007, PVP2007-26409 (CD-R)
9. Shoji Y and Sawa T, "Self-loosening mechanism of nuts due to impacts," Proceedings of PVP 2008, PVP2008-61221 (CD-R)
10. Shoji Y and Sawa T, "Self-loosening Mechanism of Nuts due to Cyclic Thermal Load," Proceedings of PVP 2009, PVP2008-77447 (CD-R)
11. Junker G. H., 1969, "New Criteria for Self-Loosening of Fasteners Under Vibration," SAE Paper 690055, pp.314-335
12. National Aerospace Standard 3350 and 3354, 1992.
13. Abaqus Analysis User's Manual V6.9, 2009
14. .Japan Industrial Standards, JIS A0001, 2009
15. Brochure of HARD LOCK Industry Co. Ltd, 2004, http://www.hardlock.co.jp