# FATIGUE LIFE IMPROVEMENT BY SLIGHT PITCH DIFFERENCE IN BOLT-NUT CONNECTIONS

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**Abstract:** The bolt-nut connections are widely used in various fields. In this paper, a slight pitch difference is introduced between the bolt and nut in order to study its effect on the fatigue performance. Here, we consider that the pitch of the nut is a few microns larger than the pitch of the bolt. Fatigue experiments are conducted for three kinds of specimens with different levels of pitch differences. The obtained S-N curves show that the fatigue life is extended to about 1.5 times by introducing a suitable pitch difference. According to the detailed investigation on the fractured specimens, it is found that the fractured positions and the crack configuration are totally different for different specimens. To find out the mechanism of the improvement of fatigue strength, Finite Element Analysis is applied in order to calculate the stress amplitude and mean stress at the bottom of each engaging bolt thread.

**Keywords:** bolt-nut connections, Pitch Difference, Fatigue Strength, Finite Element Method

## INTRODUCTION

The bolt-nut connections are an important joining technique widely used in various engineering fields. The fatigue failure and self-loosening of such connections usually lead to severe accidents. For instance, a derailment of a Jet coaster happened in Osaka Japan, in 2007, which result from that a left side wheel fell off due to the fatigue fracture at the thread-connecting parts of the axle. To ensure the structure safety, the high fatigue strength, as well as, the anti-loosening performance is required. High stress concentration factors always occur at the root of bolt thread and it is not easy to improve the fatigue strength of screws. A previous study indicated that the fatigue strength may be improved depending on the pitch error [1]. The effect of the thread shape on the fatigue life of bolt has also been investigated [2]. The tapered bolts, called CD bolts (Critical Design for Fracture), are widely used because they showed higher fatigue strength experimentally [3, 4]. Hua Zhao analyzed the stress concentration factors within bolt-nut connections [5]. In terms of anti-loosening, several special nuts were invented to deal with the self-loosening problems [6-8].

This study aims to realize the combination of fatigue strength improvement and anti-loosening performance by considering one certain innovation on the screws.  A slight pitch difference $\alpha$ is introduced between the bolt and nut.  The authors previously analyzed the anti-loosening effect and stress reduction effect for the bolt and nut having a slight pitch difference by applying the finite element method [9, 10].The authors' preliminary study showed that the bolt fatigue life could be improved by introducing the pitch difference of $\alpha=\alpha_{middle}$ [11]. Moreover, in the anti-loosening study, the experiment results showed that $\alpha=\alpha_{large}$ is the most desirable pitch difference to realize the anti-loosening performance [12]. As a further research, in this paper, more detailed fatigue experiment is conducted systematically under a series of cyclic fatigue loads for three types of specimens, i.e. $\alpha=0$, $\alpha=\alpha_{middle}$ and $\alpha=\alpha_{large}$, where $\alpha=0$ represents the standard bolt-nut connections. Then, the S-N curves are obtained and the improved fatigue lives are discussed. To clarify the effect of pitch difference, the finite element method is applied to analyze the stress amplitude and mean stress at the bottom of the engaging bolt threads. The mechanism of fatigue life improvement is considered by comparing the experimental results to those obtained using the finite element method.

## EXPERIMENTAL SET-UP

### Material properties

The Japanese Industrial Standard (JIS) M16 bolts and nuts are employed, and the fatigue experiments are conducted by using the 392 kN Servo Fatigue Testing Machine. Table 1 and Table 2 show the JIS standard and the material properties of bolt and nut in this study. The normal M16 bolt and nut have the same pitch dimension as 2000 μm. Herein, the nut pitch is assumed to be $(2000+\alpha)$ μm. Three types of pitch differences: namely $\alpha=0$, $\alpha_{middle}$ and $\alpha_{large}$, are considered. The clearance between bolt and nut is assumed to have a standard dimension as 125 μm. The schematic diagram of bolt and nut is shown as Figure 1. Figure 2 illustrates the effect of the pitch difference on the contact status between bolt and nut threads when a large pitch difference is introduced.

Table 1 JIS Standards of Bolt and Nut

| | Strength grade | Yield strength (MPa) | Tensile strength (MPa) |
|---|---|---|---|
| Bolt | 8.8 | 660 | 830 |
| Nut | 8 | - | - |

Table 2 Material Properties of Bolt and Nut

| | Young’s modulus (GPa) | Poison’s ratio | Yield strength (MPa) | Tensile strength (MPa) |
|---|---|---|---|---|
| SCM435 ( Bolt) | 206 | 0.3 | 800 | 1200 |
| S45C ( Nut) | 206 | 0.3 | 530 | 980 |

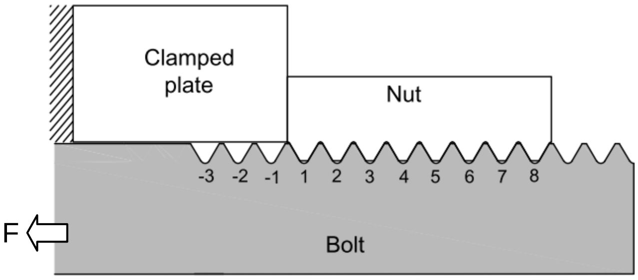


Fig.1 Schematic diagram of bolt joint

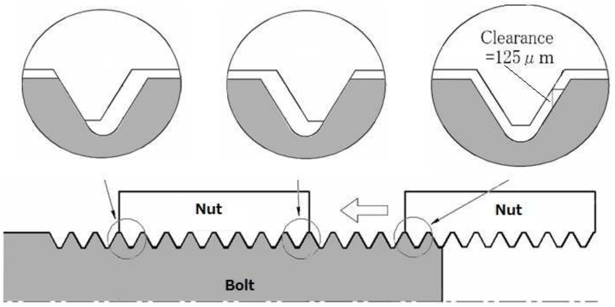


Fig.2 Contact status between bolt and nut considering pitch difference

**Fatigue tests**

The experimental device used in the fatigue tests is shown in Figure 3. The bolt specimens are subjected to a series of repeated loadings. Table 3 shows the experimental loading conditions and the corresponding stress according to the bottom cross sectional area of the bolt $A_R$=141 mm$^2$. The cycling frequency of the loadings is 8 Hz. The stress amplitude under which the specimen sustains $2\times10^6$ stress cycles before failure occurs is considered as the fatigue limit.

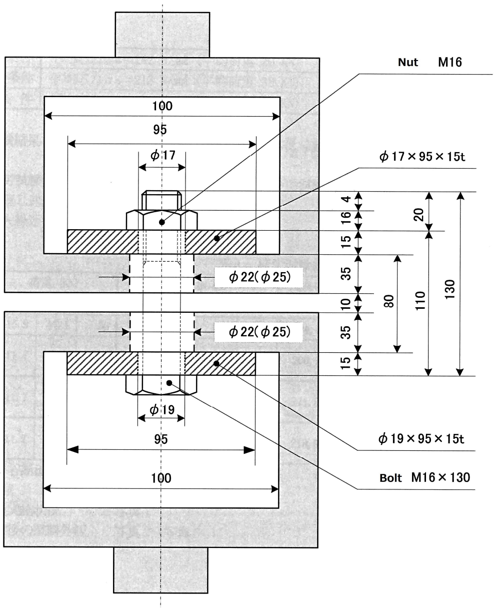


Fig.3 Experimental device

Table 3 Experimental loading conditions

| Load (kN) | | Stress (MPa) | |
|---|---|---|---|
| Mean load | Load amplitude | Mean stress | Stress amplitude |
| 30 | 22.6 | 213 | 160 |
| 30 | 18.3 | 213 | 130 |
| 30 | 14.1 | 213 | 100 |
| 30 | 11.3 | 213 | 80 |
| 30 | 8.5 | 213 | 60 |
| 30 | 7.1 | 213 | 50 |

## EXPERIMENTAL RESULTS

Figures 4-6 show the fractured specimens subjected the stress amplitude $\sigma_a$=100 MPa. For the standard bolt-nut connection, it is confirmed that the fracture always occurs at the bottom of the first thread as shown in Figure 4. For the specimens of $\alpha=\alpha_{middle}$ and $\alpha=\alpha_{large}$, the fracture position are between thread No.1 and thread No.3 of bolt. The fracture surfaces also show obvious different characteristics as varying the pitch differences.

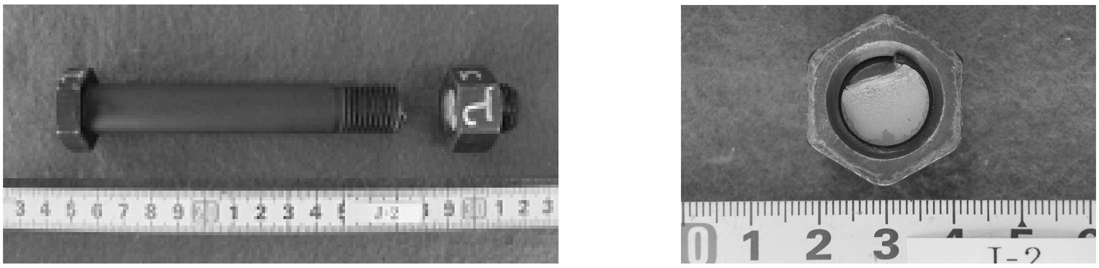


Fig.4 Specimen ($\alpha$=0, $\sigma_a$=100MPa)

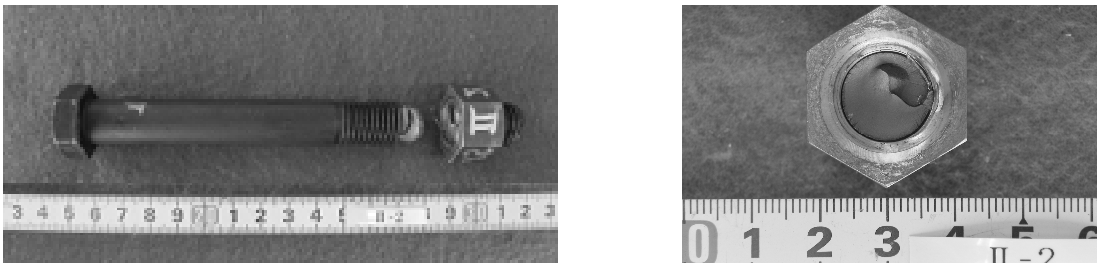


Fig.5 Specimen ($\alpha$=$\alpha_{middle}$, $\sigma_a$=100MPa)

Fig.6 Specimen ($\alpha$=$\alpha_{large}$, $\sigma_a$=100MPa)

The *S*-*N* curves with fatigue limit at $N$=2×$10^6$ stress cycles are obtained as shown in Figure 7. It is found that the fatigue lives are clearly depending on the three levels of pitch differences. Table 4 shows the enhancement ratio of the fatigue life normalized by the results of $\alpha$=0. When the stress amplitude is above 80 MPa, the fatigue life for $\alpha$=$\alpha_{middle}$ is about 1.5 times and the fatigue life for $\alpha$=$\alpha_{large}$ is about 1.2 times of the standard bolt-nut connections ($\alpha$=0). However, near the fatigue limit, the fatigue lives of the three types of specimens are similar, and the fatigue limits remain at the same value of 60 MPa.

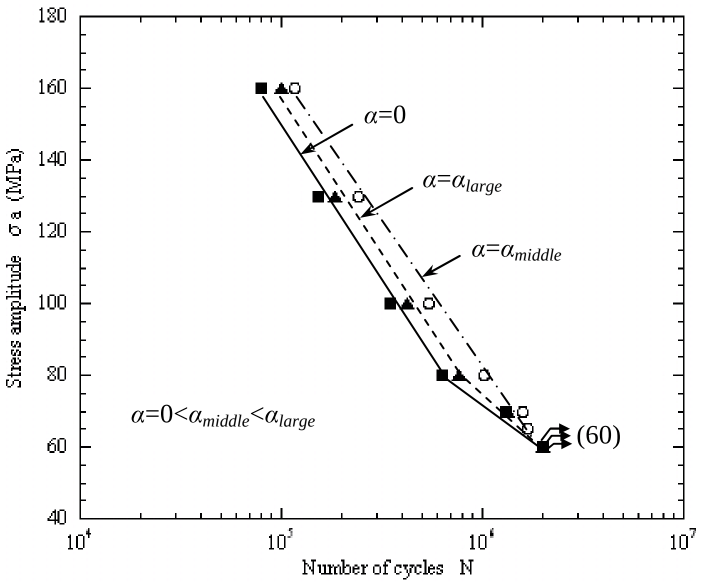


Fig. 7 *S*-*N* curves

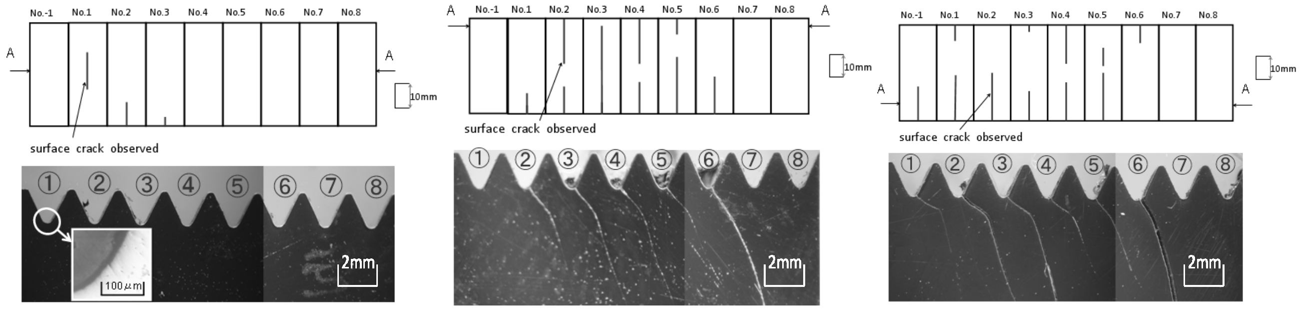
Table 4 Enhancement ratio of the fatigue life

| Pitch Difference $\alpha$ (μm) | Stress amplitude $\sigma_a$ (MPa) | | | | |
|---|---|---|---|---|---|
| | 160 | 130 | 100 | 80 | 70 |
| 0 | 1 | 1 | 1 | 1 | 1 |
| $\alpha_{middle}$ | 1.49 | 1.60 | 1.53 | 1.61 | 1.21 |
| $\alpha_{large}$ | 1.26 | 1.22 | 1.20 | 1.21 | 1.02 |

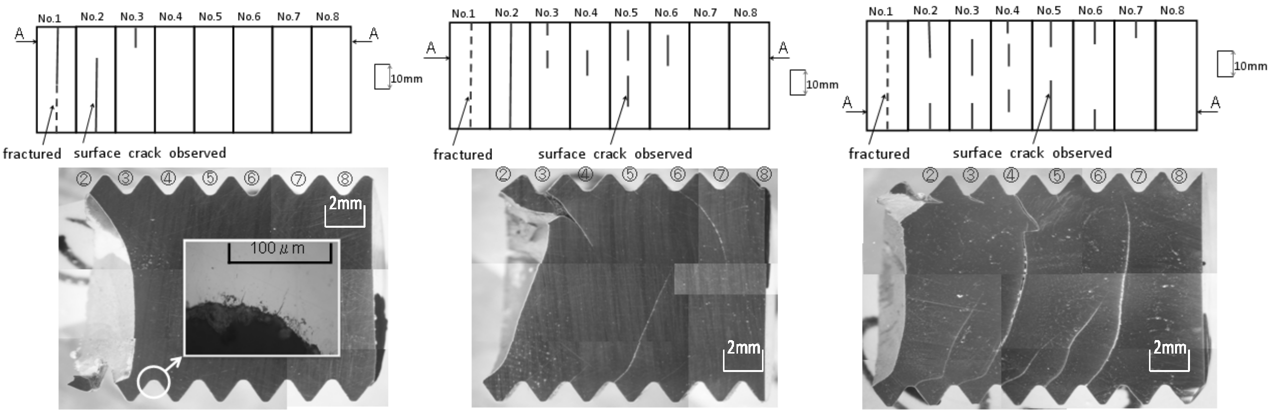
## CRACK OBSERVATION

Figure 8 shows the observed trajectory of cracks along the longitudinal cross section of the specimens at the fatigue stress amplitudes $\sigma_a$=60 MPa, 70 MPa, 100 MPa and 160 MPa. For $\alpha$=0, small cracks occur at thread No.1 and thread No.2. For $\alpha=\alpha_{middle}$ and $\alpha=\alpha_{large}$, large cracks occur between thread No.2 and thread No.7. Moreover, with increasing the stress amplitude, the cracks show different shapes indicating changes in mode mixity.

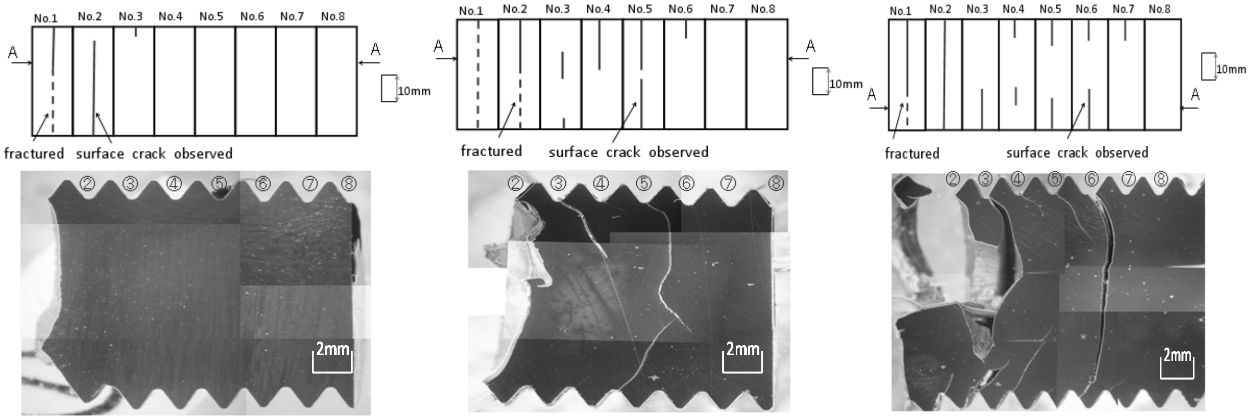
It can be seen in Figure 8 that for the standard bolt-nut connections, the crack occurs at thread No.1 causing finial fracture. However, for the specimens of $\alpha=\alpha_{middle}$ and $\alpha=\alpha_{large}$, the initial cracks start at thread No.5 or thread No.6, extending toward thread No.1 and finally fracture happen nearby thread No.1. From the S-N curves in Figure 7 and the observations of crack trajectories in Figure 8, we can conclude that the fatigue life of the bolt-nut connections may be extended by introducing a pitch difference because the changes in crack propagation trajectory may take place.



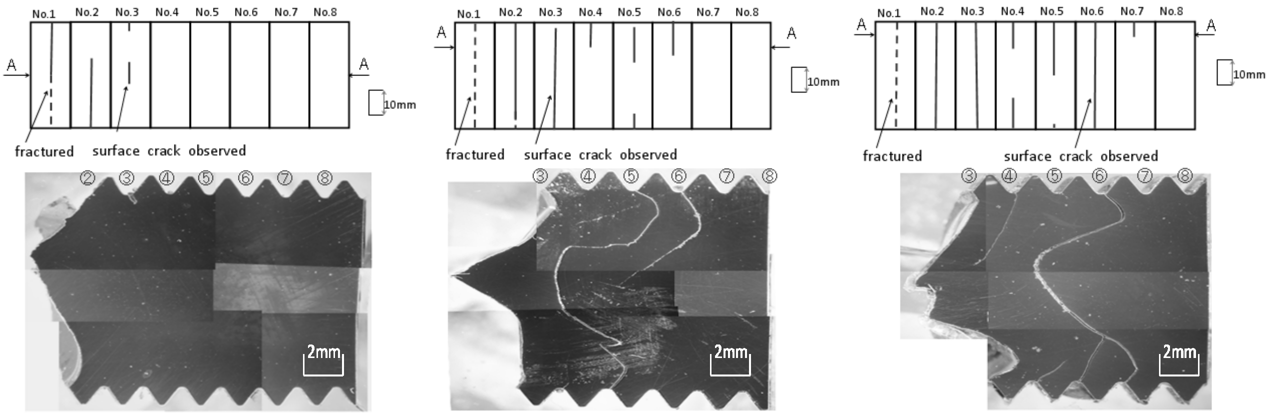
($\alpha=0$, $\sigma_a=60$ MPa) ($\alpha=\alpha_{middle}$, $\sigma_a=60$ MPa) ($\alpha=\alpha_{large}$, $\sigma_a=60$ MPa)



($\alpha=0$, $\sigma_a=70$ MPa) ($\alpha=\alpha_{middle}$, $\sigma_a=70$ MPa) ($\alpha=\alpha_{large}$, $\sigma_a=70$ MPa)



($\alpha=0$, $\sigma_a=100$ MPa) ($\alpha=\alpha_{middle}$ , $\sigma_a=100$ MPa) ($\alpha=\alpha_{large}$, $\sigma_a=100$ MPa)



($\alpha$=0, $\sigma_a$=160 MPa) ($\alpha$=$\alpha_{middle}$, $\sigma_a$=160 MPa) ($\alpha$=$\alpha_{large}$ , $\sigma_a$=160 MPa)

Fig. 8 Observation of crack trajectories

## FINITE ELEMENT ANALYSIS

### Stress analysis at bottom of bolt thread

To analyze the stress state at the bottom of the bolt threads, finite element models are created by using Finite Element Method (FEM) with MSC.Marc/Mentat 2007. Three models have different pitch differences, i.e. $\alpha$=0, $\alpha$=$\alpha_{middle}$ and $\alpha$=$\alpha_{large}$, in accordance with the experimental configurations of the test specimens. Figure 9 shows the axisymmetric model of the bolt-nut connection and the clamped plate. Figure 10 shows the local coordinate at the bottom of bolt thread. An elastic-plastic analysis is performed for three models under the same load, i.e. $F$=30±14.1 kN. The material properties listed in Table 2 are used in the calculation and Figure 11 illustrates the stress strain relation for SCM435 and S45C. The coefficient of friction between bolt and nut is 0.3. Figure 12 shows the stress variations for $\sigma_\psi$, $\sigma_\theta$ and the equivalent von-Mises stress $\sigma_{eq}$ at each bolt tread from thread No.5 to thread No.8. Herein, the stress variation $\sigma_\psi$ is taken into account and the position of the maximum stress amplitude is marked as shown in Figure 12. As indicated in Figure 12, at each bolt thread from thread No.3 to thread No.8, the maximum stress amplitude and the mean stress are investigated at the point where the maximum stress amplitude appears. The endurance limit diagrams are obtained as shown in Figure 13. In the endurance limit diagram, the Soderberg line [13] is plotted. Herein, the point $\sigma_w$ represents the fatigue strength corresponding to the case of complete reversal ($\sigma_m$ =0), and the point $\sigma_{sl}$ corresponds to the yield strength. It should be noted that because of the stress gradient, the maximum stress amplitude for fracture of notched specimens is always larger than that of the plain specimens. Therefore, the stress data plotted beyond the line ( $(\sigma_m/\sigma_{sl})+(\sigma_a/\sigma_w)>1$ ) does not represent the real fracture at the bolt thread.

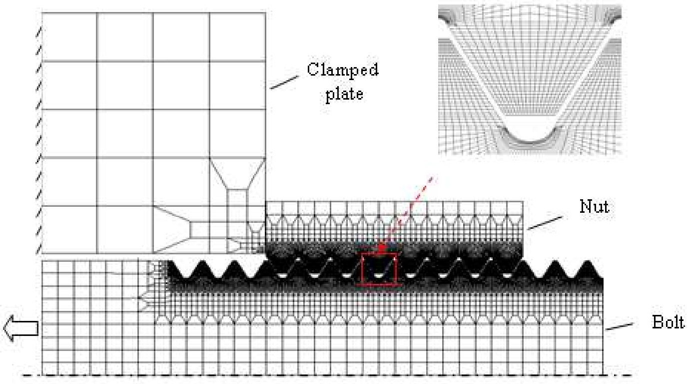


Fig. 9 Axisymmetric finite element model of bolt-nut connections

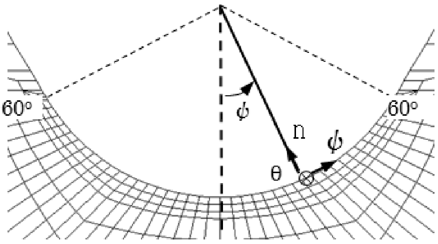


Fig. 10 Local coordinate at bottom of bolt thread

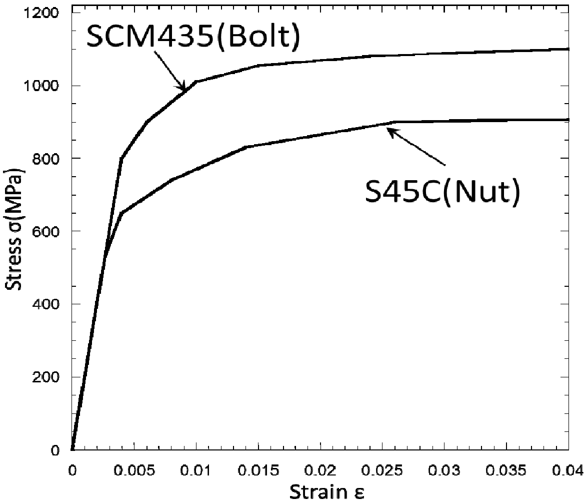
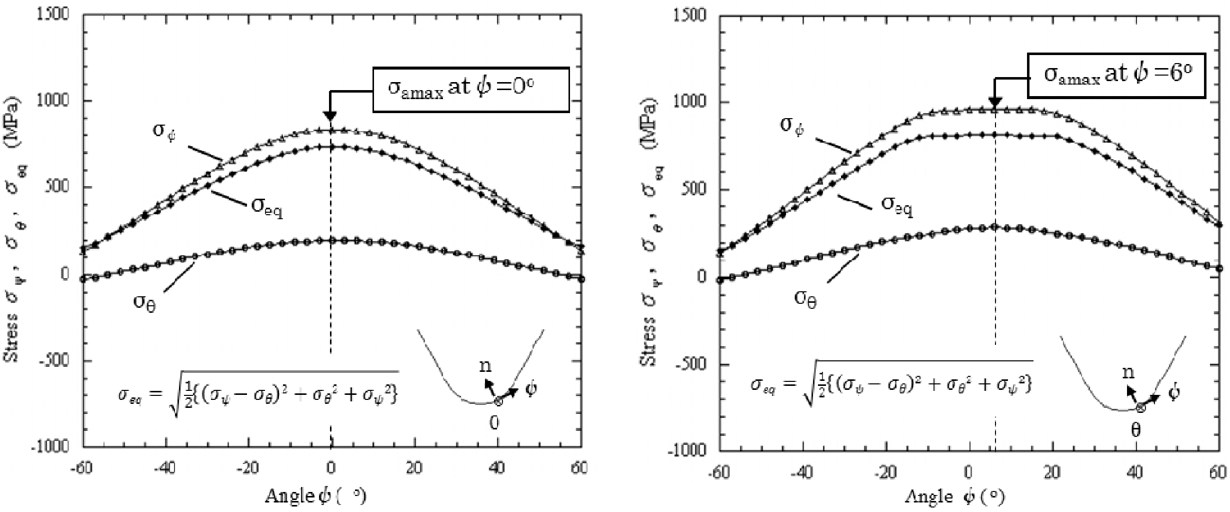
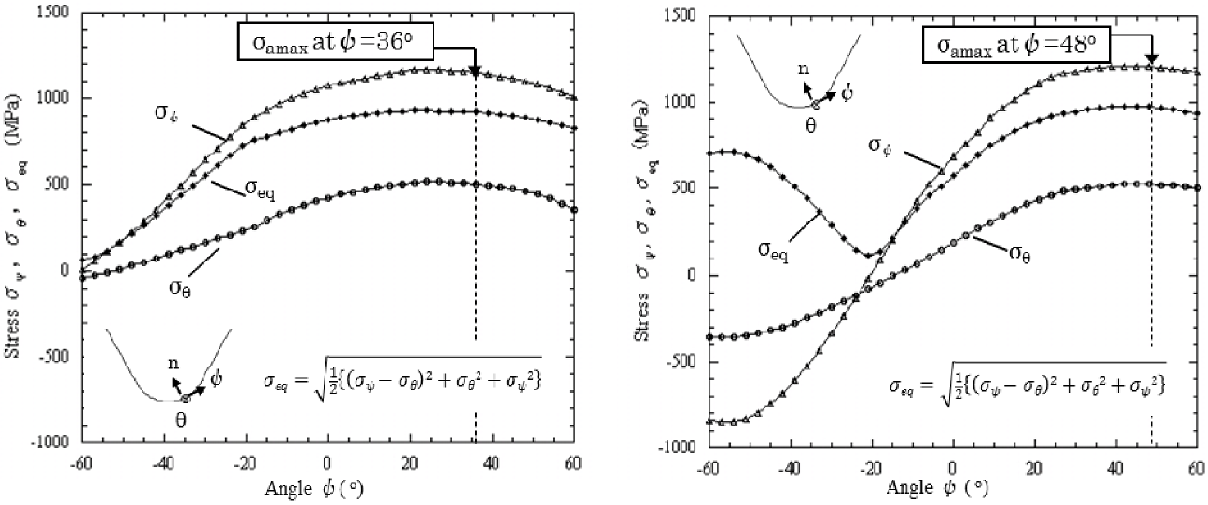


Fig. 11 Stress strain relation for SCM435 and S45C



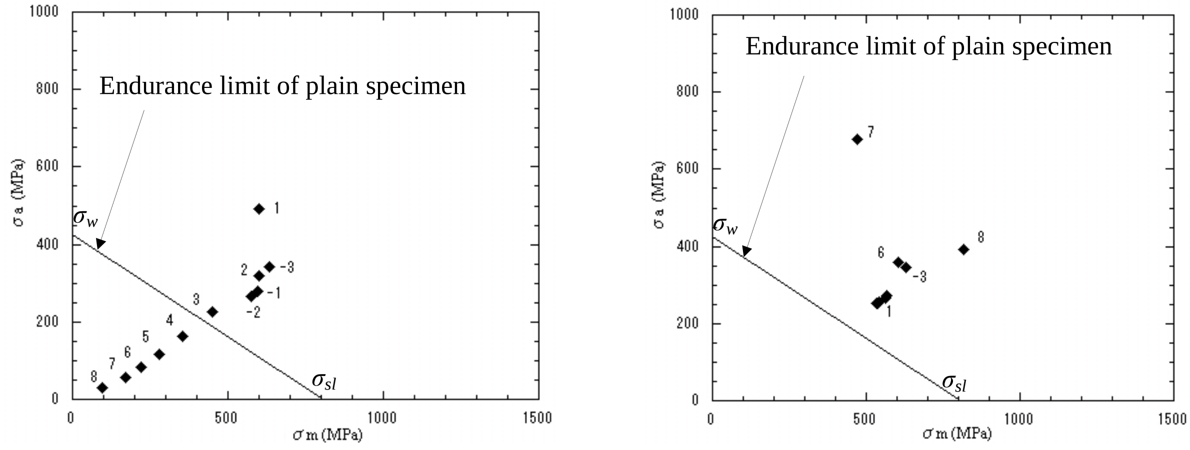
(a) Stress at bottom of thread No.5 (b) Stress at bottom of thread No.6



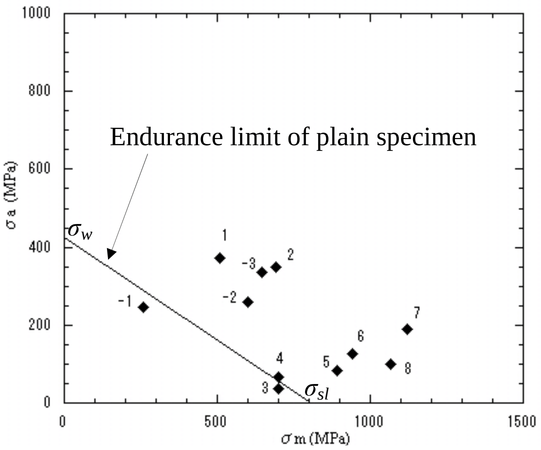
(c) Stress at bottom of thread No.7 (d) Stress at bottom of thread No.8

Fig.12 Stress at bottom of thread ($\alpha=\alpha_{middle}$, $F$=30+14.1 kN)

From Figure 13(a), it can be seen that for the standard bolt-nut connections, the bottom of thread No.1 has the highest stress amplitude, which corresponds to the fracture position in the fatigue experiment as illustrated previously. In Figure 13(b), when a pitch difference of $\alpha=\alpha_{middle}$ is introduced, on one hand the stress amplitude decreases at the bottom of thread No.1 and on the other hand, the stress amplitude at threads No.6, No.7 and No.8 increases significantly. For $\alpha=\alpha_{large}$, the severe stress state occurs nearby threads No.1 and No.7 as shown in Figure 13(c).



(a) $\alpha$=0 , $\sigma_a$=100 MPa (b) $\alpha=\alpha_{middle}$, $\sigma_a$=100 MPa



(c) $\alpha=\alpha_{large}$, $\sigma_a$=100 MPa

Fig. 13 Endurance limit diagrams

## Effects of incomplete thread and Clearance

The analysis shows that by introducing $\alpha=\alpha_{middle}$, high stress appears at threads No.7 and No.8. However, the crack observation shows that the initial crack occurs at thread No.5 instead of threads No.7 and No.8. In order to further investigate these results, the effects of the incomplete thread and the clearance between bolt and nut on the stress state are discussed. Figure 14 shows the FE model for the incomplete thread bolt. Figure 15(a) shows a comparison between the results for the incomplete and complete threads. It is found that the stress amplitude at threads No.7 and No.8 decreases and the stress amplitude at thread No.6 increases by considering incomplete thread. In Figure 15(b), the effect of clearance (see Figure 2) is indicated by comparing the results for clearance of 125 µm and 250 µm. In this experiment, the clearance between the bolt and nut is controlled at 125 µm, however, the nut may be inclined and the clearance become larger, i.e. 250 µm. Figure 15(b) shows that with increasing the clearance the stress amplitude at threads No.7 and No.8 decreases and the stress amplitude at thread No.6 increases. This may explain the reason why no crack is observed at threads No.7 and No.8 and crack initiates around thread No.5.

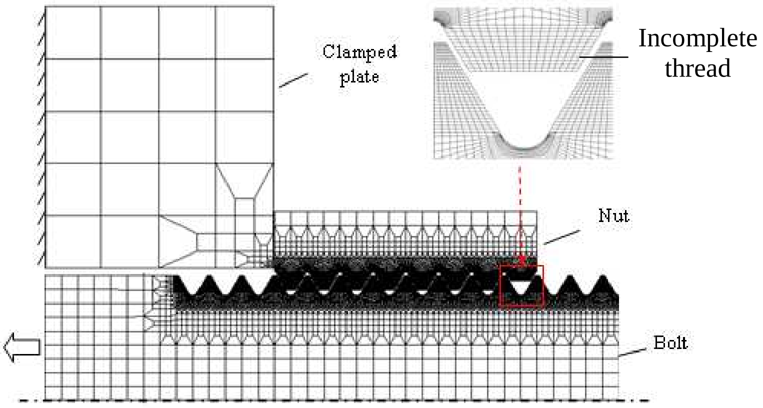
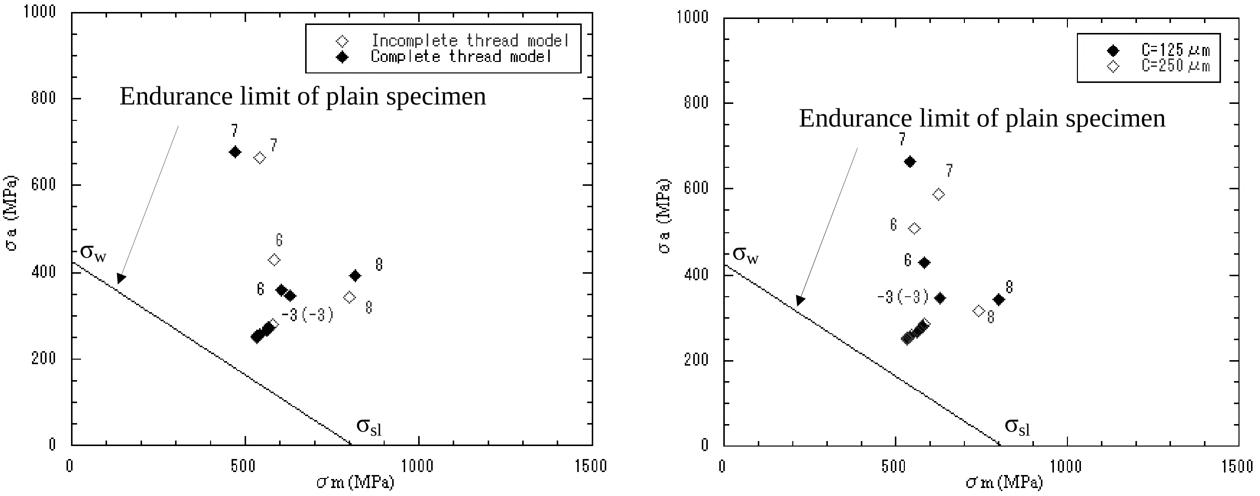


Fig. 14 Axisymmetric finite element model for incomplete thread



(a) Incomplete thread model vs complete thread model

(b) Clearance=125 µm vs clearance=250 µm

Fig. 15 Endurance limit diagram ($\alpha=\alpha_{middle}$, $\sigma_a$=100MPa)

## CONCLUSIONS

In this study, a slight pitch difference $\alpha$ is designed between the M16 bolt-nut connections. The fatigue experiment has been conducted for three levels of pitch difference, i.e. $\alpha$=0; $\alpha=\alpha_{middle}$ which has been studied previously that it has an effect on the fatigue life improvment, and $\alpha=\alpha_{large}$ which is the most desirable pitch difference to realize the anti-loosening performance in the previous anti-loosening study. The effect of pitch difference on the stress state at the bottom of the bolt threads has been numerically analyzed using the finite element method. The conclusions can be summarized as follows:

(1) It is found that $\alpha=\alpha_{middle}$ is the most desirable pitch difference to extend the fatigue life of the bolt-nut connection. Compared with the standard bolt-nut connection, the fatigue life for $\alpha=\alpha_{middle}$ can be extended to about 1.5 times.

(2) It is found that the stress amplitude at the bottom of thread No.1 decreases significantly when a pitch difference is introduced. For $\alpha=\alpha_{middle}$, the FEM results shows that high stress amplitude occurs at the bottom of threads No.6, No.7 and No.8, which almost corresponds to the experimental observations.

(3) For the specimens with $\alpha=\alpha_{middle}$, it is found that the crack occurs at thread No.5 in the first place, then extends toward thread No.1 until final fracture happens nearby thread No.1. Therefore, the fatigue life of the bolt is extended compared with the standard bolt-nut connection.

(4) To investigate the reason why in FEM analysis high stresses appear at threads No.7 and No.8, while in the experimental observation the cracks happen at thread No.5, the effects of the incomplete thread and the clearance between bolt and nut on the stress state are investigated. The simulation results of the incomplete model and the large clearance model show that compared to the normal model, the stress amplitude at threads No.7 and No.8 decreases, while the stress amplitude at thread No.6 increases, which is closer to the experimental results.

The M16 bolt-nut connections (JIS) are employed here as the study objective. The extended study will discuss more connections of different sizes in a further research.

## ACKNOWLEDGEMENT

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