Experimental study on the effect of shape of bolt and nut on fatigue strength for bolted joint

PAPER • OPEN ACCESS

Experimental study on the effect of shape of bolt and nut on fatigue strength for bolted joint

To cite this article: T Matsunari *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **372** 012016

View the article online for updates and enhancements.

Related content

- 3D finite element analysis of tightening process of bolt and nut connections with pitch difference
X Liu, N-A Noda, Y Sano et al.

- Fatigue Test of Piezoelectric Ceramics under High Hydrostatic Pressure
Sumio Takahashi, Katsunori Okajima and Akio Hasegawa

- Suitable pitch difference to realize anti-loosening performance for various bolts-nuts diameter
S Kubo, K Tateishi, N-A Noda et al.

Experimental study on the effect of shape of bolt and nut on fatigue strength for bolted joint

T Matsunari[1], K Oda[2,5], N Tsutsumi[2], T Yakushiji [3], N A Noda[4] and Y Sano[4]

[1]Graduate School of Engineering, Oita University, 700 Dannoharu, Oita 870-1192, Japan
[2]Division of Mechanical Engineering, Oita University, 700 Dannoharu, Oita 870-1192, Japan
[3]National Institute of Technology, Oita College, 1666 Maki, Oita 870-0152, Japan
[4]Mechanical Engineering Department, Kyushu Institute of Technology, 1-1 Sensui-cho Tobata-ku, Kitakyushu-shi, 804-8550, Japan

E-mail: oda-kazuhiro@oita-u.ac.jp

Abstract. In this study, the effect of curvature radius of the thread bottom and the pitch difference between of M16 bolt and nut on fatigue strength for bolted joint is considered experimentally. The M16 bolt-nut specimens having the two kinds of thread bottom radii and the pitch differences are prepared. The S-N curves for bolted specimens with different thread shapes are obtained by the stress-controlled fatigue test (stress ratio R>0). The experimental results are compared and discussed in terms of stress analysis. The finite element method is used to make a simulation of the fatigue experiment and the mean stress and stress amplitude at each thread bottom of bolt are analysed. It is found that the initiation and propagation of crack are changed by introducing the pitch difference of α=15 μm, from the crack observation in cross section of the bolt specimens after the experiment. Furthermore, the fatigue life can be extended by increasing curvature radius of thread bottom and introducing the pitch difference.

1. Introduction

The bolted connection is one of the most important mechanical components and is used frequently. For instance, since about 1,000 bolts and nuts joints are used in a single car, high fatigue strength at low cost is required. Damage of the bolt-nut joint is due to high stress concentration at the bolt thread bottoms and its strength is reduced. To ensure the safety and reliability of the bolted joint, researches on anti-loosening performance have been actively conducted [1-3]. However, there are not many studies on fatigue strength improvement of bolted connections. It is not easy to improve the fatigue strength of standard shape of bolt-nut joint because high stress concentration always occurs at the bottom of bolt thread.

Focusing on the stress relaxation at the thread bottom due to the shape change of the bolt [4-7] and the material difference of the fatigue strength [8], several studies have been conducted to improve the fatigue strength of the bolted joint. The effect of the pitch difference between the nut and the bolt on the stress concentration at the screw thread of the bolt has been studied previously and it is reported that the fatigue strength can be improved by changing the contact state between the bolt and the nut [9-14]. In particular, Noda *et al* [9-13] analysed the effects of anti-loosening and stress reduction for the bolt-nut joint with small pitch difference, and showed that the fatigue life of the bolted joint can be

improved by using the pitch difference of α=15 μm. However, the studies on the conventional pitch difference were limited to the improvement of fatigue life for the standard shape bolt thread.

In this study, a more detailed fatigue test is systematically carried out for a new bolt specimen with small pitch difference α and large thread bottom radius ρ. Here, the standard bolt-nut joint has α=0 and ρ=ρ$_0$. Then, from the S-N curves obtained for the bolted specimens, the improved fatigue lives are discussed. To clarify the effects of the thread bottom radius and the pitch difference, stress amplitude and average stress at each bolt thread are analysed by the finite element method (FEM). By comparing the experimental results with the results computed using FEM, the mechanism of improvement in fatigue life of bolted specimen is examined.

2. Fatigue experiment to investigate the fatigue life

2.1. Specimens and experimental conditions

In this study, the Japanese Industrial Standard (JIS) M16 bolt-nut joints of strength grade 8.8 are used. The bolt is made from chromium-molybdenum steel SCM435, and the nut is the quenched and tempered medium carbon steel S45C, and their properties are indicated in table 1. Figure 1 shows schematic diagram of bolted joint. Numbers -3, -2 … 7, 8 in figure 1 correspond to the bottom of each thread. The fatigue experiment device assembly drawing is illustrated in figure 2. The Servo Fatigue Testing Machine (392 kN) is used at a cycle frequency of 5 or 10 Hz in this test. The bolt specimen is subjected to a mean tensile force of 30 kN. Since the area A_R of the bolt cross section is 141 mm^2, the stress-controlled fatigue experiment is conducted under the corresponding mean tensile stress $σ_m$=213 MPa. The stress amplitude in the fatigue test is set in the range of 50 MPa to 160 MPa. The S-N curves are obtained with five stress amplitudes and the fatigue limit of 2×10^6 cycles.

Table 1. Mechanical properties of bolt and nut specimen.

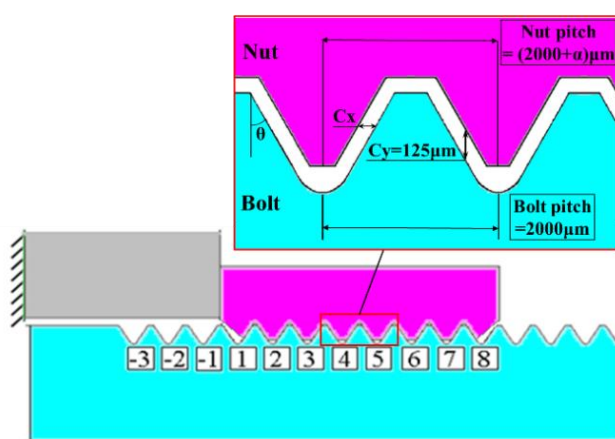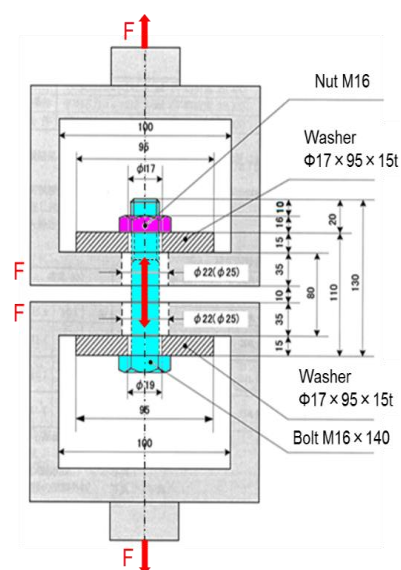|	Young's modulus (GPa)	Poison's ratio	Yield strength (MPa)	Tensile strength (MPa)
SCM435 (Bolt)	206	0.3	800	1200
S45C (Nut)	206	0.3	530	980

Figure 1. Schematic view of bolted joint.

Figure 2. Schematic illustration of fatigue test.

2.2. Effect of pitch difference of the standard bolt-nut joint

In the previous study, Noda et al. have reported that the effect of the pitch difference on the fatigue strength in bolted joint [9-13]. The standard M16 bolts and nuts usually have the same pitch dimension of 2000 μm. For different pitch joint, the pitch dimension of the nut is set to be equal or slightly larger than the bolt pitch, that is, 2000 μm+α. Three types of bolted joint specimens of α=0, 15 and 33 μm are investigated. The bolt-nut clearance is assumed to be the standard dimension of 125 μm.

The S-N curves for bolted joints having the pitch difference α are shown in figure 3. It is found that the fatigue lives of bolt-nut joints with the three levels of pitch difference are different clearly. When the stress amplitude is above 80 MPa, the fatigue lives of the bolted joints for α=15 μm and 33 μm are about 1.4 times and 1.2 times larger than that of the standard bolted joint for α=0. However, near the fatigue limit at $N=2\times10^6$ cycles, the fatigue lives of three different pitch specimens are not very different, and the fatigue limit for three levels of pitch difference remains the same value of 60 MPa.
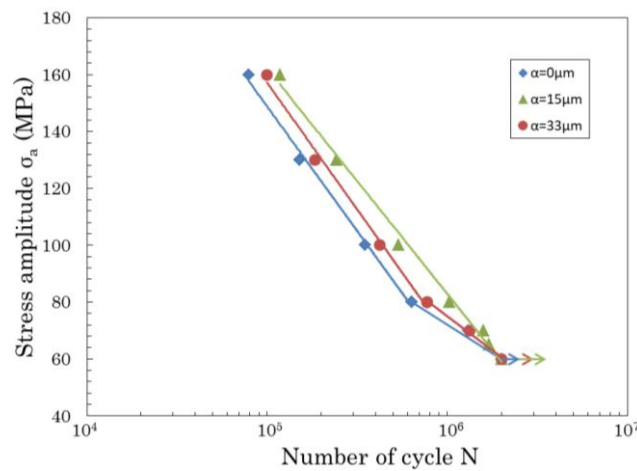

Figure 3. S-N curves for bolt-nut joints having the pitch difference α=0, 15, 33 μm when ρ=ρ₀.

2.3. New bolt-nut joint with larger thread bottom radius and slight pitch difference

Next, we focus on the effect of the radius of the thread bottom on the fatigue strength of bolted joint. Newly shaped bolt specimens having the thread bottom radius $2\rho_0$ are prepared. Figure 4 shows the shapes and dimensions of the standard and the new bolt-nut joints when the pitch difference is α=0. The stress concentration factors K_t for cylindrical bar having a 60° V-shaped circumferential notch under tension are shown in figure 4. The stress concentration factor decreases considerably from $K_t = 4.53$ ($\rho=\rho_0$) to $K_t = 2.90$ ($\rho=2\rho_0$) by doubling the thread bottom radius.

(a) Normal bolt thread ($\rho=\rho_0$, K_t=4.53)   (b) Large bolt thread ($\rho=2\rho_0$, K_t=2.90)

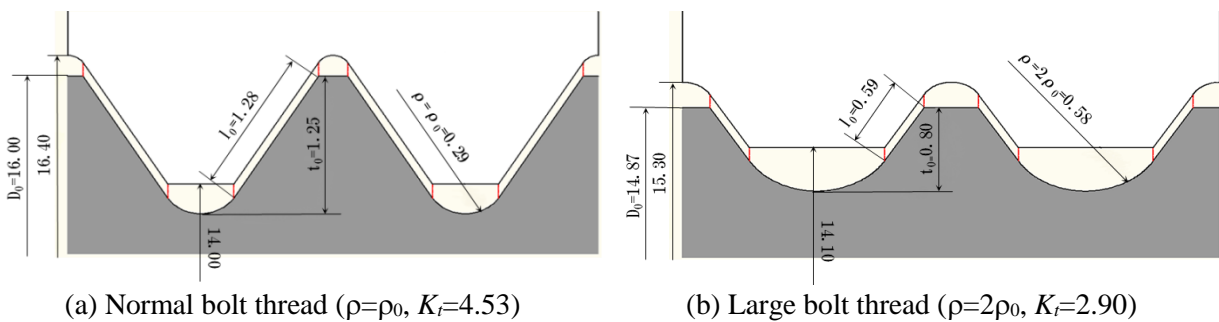**Figure 4.** Two types of bolt specimens with different thread shapes.

Figure 5 indicates the S-N curves for the two types of bolt specimens, $\rho=\rho_0$ and $2\rho_0$, when the pitch

difference is α=0. From figure 5, it is found that the fatigue life for the newly shaped bolt (ρ=2ρ$_0$) is improved to more than 2 times that for the standard bolt specimen (ρ=ρ$_0$). Furthermore, the fatigue limit is about 30% larger than that of the normal bolt-nut joint.
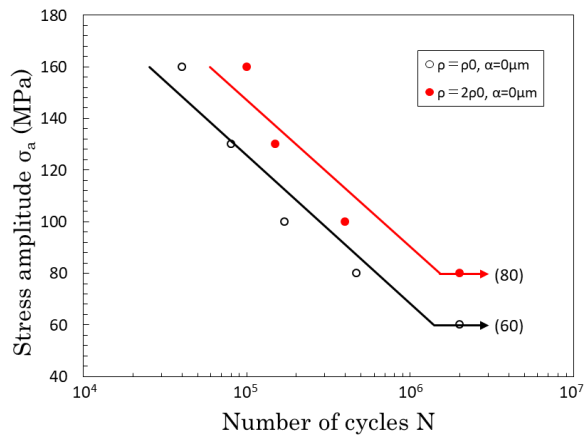

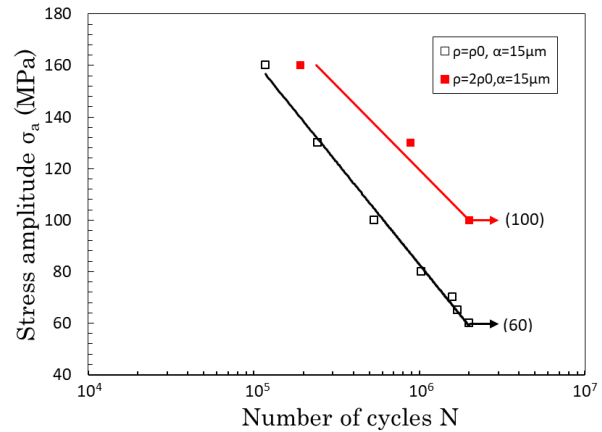**Figure 5.** S-N curves for bolted joints with different thread bottom radius ρ=ρ$_0$ and 2ρ$_0$ when α=0.

Figure 6. S-N curves for bolted joints with different thread bottom radius ρ=ρ$_0$ and 2ρ$_0$ when α=15 μm.

Figure 6 shows the S-N curves for the two types of bolt-nut joints when the pitch difference α=15 μm. In the case that the bolted joints have the pitch difference of α=15 μm, the fatigue life of the new bolted joint with ρ=2ρ$_0$ is over 2 times longer than that of the normal shaped bolt ρ=ρ$_0$. By doubling the thread bottom radius and applying the pitch difference of α=15 μm, the fatigue limit for the bolt-nut joint is improved to 100 MPa.

2.4. Crack observation to investigate the fatigue life improvement mechanism
Figure 7 shows the example of the fractured specimens with the different thread shape and pitch difference when σ$_a$=100 MPa. In figure 7, N_f means the number of cycles until the specimen breaks.
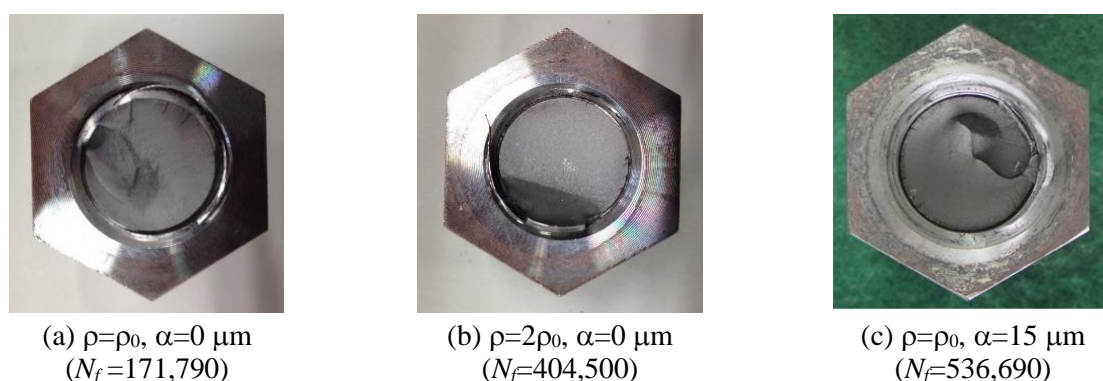

(a) ρ=ρ$_0$, α=0 μm   (b) ρ=2ρ$_0$, α=0 μm   (c) ρ=ρ$_0$, α=15 μm
(N_f =171,790)   (N_f=404,500)   (N_f=536,690)

Figure 7. Fracture surface of the broken specimens (σ$_a$=100 MPa).

Figure 8 also indicates the longitudinal cross section photo and the crack trajectories observed from the surface of fractured bolt specimens. For α=0, cracks occur at No. 1 and No. 2 threads as shown in figures 8(a) and 8(b). For α=15 μm, cracks occur between No. 2 and No. 6 threads as illustrated in figure 8(c). It can be seen that for the bolted joints with normal pitch α=0, the crack initiates at No. 1 thread or No. 2 thread causing final fracture. On the other hand, for the specimen of α=15 μm, the

cracks initiate at No. 5 thread or No. 6 thread, extending toward No. 1 thread and finally fracture occurs nearby No. 1 thread. From the S-N curves and the crack observation in figures 6 and 8, it is concluded that the fatigue life of the bolt-nut connection can be improved by introducing the suitable pitch difference and thread bottom radius because the initiation and the propagation of cracks may be changed.
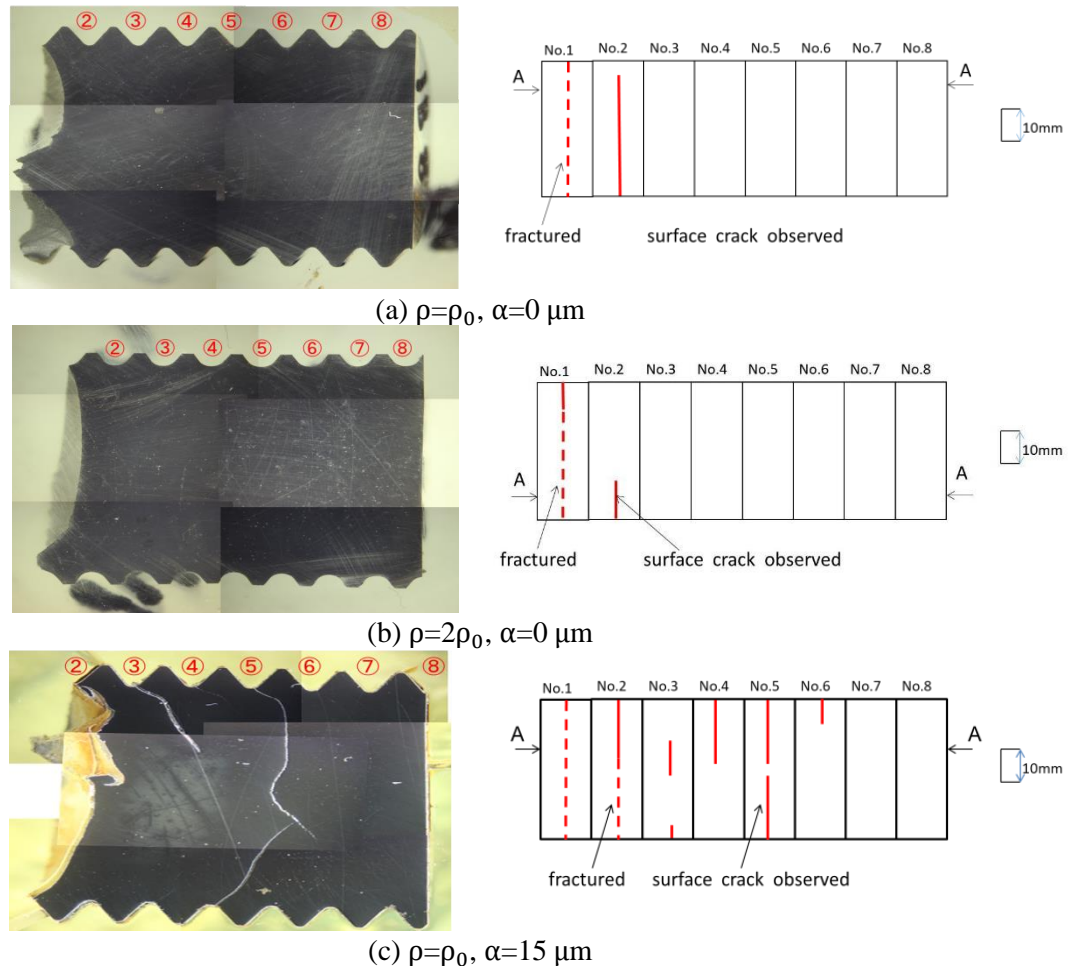

(a) ρ=ρ$_0$, α=0 μm

(b) ρ=2ρ$_0$, α=0 μm

(c) ρ=ρ$_0$, α=15 μm

Figure 8. Crack configuration observed from the surface of the fractured specimens (σ_a=100 MPa).

3. Stress state at bolt thread bottom

3.1. Analysis model and conditions

The stress state at each bottom of the bolt thread is investigated by the finite element analysis. The axisymmetric FEM model of bolt-nut joint is illustrated in figure 9. The versatile FEM code MSC.Marc/Mentat 2012 is used for analysis. A four-node axisymmetric solid element is adopted and the minimum element size is 0.015 mm × 0.01 mm near the thread bottom of the bolt. The FEM models have different pitches and thread bottom radii, i.e. α=0, 15 μm and ρ= ρ$_0$, 2ρ$_0$ according to the experimental arrangements of the bolt-nut specimens. The material properties of bolt and nut listed in table 1 are applied in the calculation. An elastic-plastic analyses for FEM models are performed under the same loading conditions as experiment. The clamped plate is fixed horizontally and the axial force F=30±14.1 kN is applied to the bolt head. The force amplitude F_a=14.1 kN corresponds to the nominal stress amplitude σ_a=100 MPa in the minimum section of the bolt.

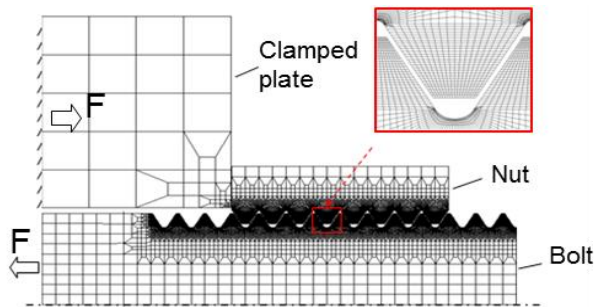**Figure 9.** Axisymmetric FEM model.

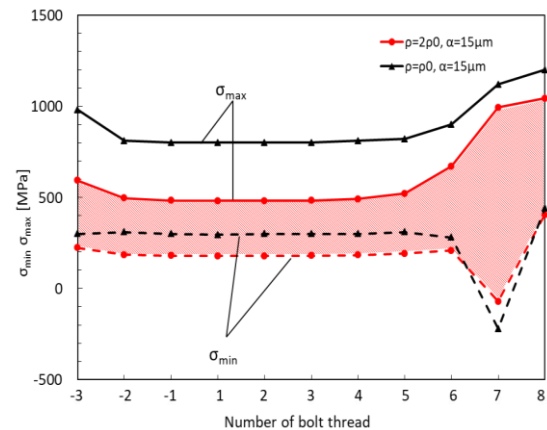**Figure 10.** σ_{max} and σ_{min} at each bolt thread.

3.2. Maximum stress amplitude at bottom of bolt thread

Figure 10 shows the maximum and minimum stresses at each thread bottom of the bolt when α=15 μm. In figure 10, σ_{max} is the maximum stress at each thread bottom under the force *F*=30+14.1 kN and σ_{min} is the minimum stress at each thread bottom under the force *F*=30-14.1 kN. The black line shows the values for standard bolt ($\rho = \rho_0$) and the red line is the values for newly shaped bolt ($\rho = 2\rho_0$). The mean stress σ_m and the stress amplitude σ_a are obtained by

$$\sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2}, \ \sigma_a = \frac{\sigma_{max}-\sigma_{min}}{2} \tag{1}$$

The previous study [13] has reported that the highest stress amplitude appears at the bottom of No. 1 thread when α=0 μm. On the other hand, when the pitch difference of α=15 μm is introduced, the stress amplitude decreases at the bottom of No. 1 and the highest stress amplitude occurs at No. 7 thread. This is roughly in agreement with the crack observation in the fatigue experiment shown in figure 8. As indicated by the red range in figure 10, the stress amplitude σ_a and the mean stress σ_m at the bottom of all threads are reduced by doubling the thread bottom radius of the bolt.

From the figures 8 and 10, by introducing the suitable pitch difference, the load distribution of each thread of bolt is changed, and the fatigue life extends due to the change of crack initiation and propagation. Furthermore, by increasing the thread bottom radius of bolt, the fatigue life and the fatigue limit are greatly improved because the stress amplitude and the mean stress at each bolt thread decrease.

4. Conclusions

In this study, the effect of the pitch difference and large radius of bolt thread bottom on fatigue strength of bolted joint was examined using experimental technique. The fatigue test was conducted by using the bolt-nut specimens having the different pitches and thread bottom radii to investigate the fatigue life and the fatigue limit. The conclusions can be summarized as follows:

- The fatigue life was improved significantly by increasing the radius of bolt thread and introducing the slight pitch difference. As compared with the standard bolt-nut joint, the fatigue limit of newly shaped bolt joint was also improved to about 1.5 times.
- From the crack observation, it was found that the crack propagation path changes by introducing pitch difference. In the case of the pitch difference α=15 μm, cracking started from No. 5 or No. 6 thread and the final fracture occurred at No. 1 or No. 2 because the load distribution of each thread of bolt was changed.
- The FEM analysis showed that the stress amplitude and the mean stress at each bolt thread decrease by increasing the thread bottom radius of bolt when the pitch difference is α=15 μm. Therefore, the present method is effective for improving the fatigue strength of the bolt-nut

joint.

References

[1]   Hard Lock Kogyo K K 2002 Hard Lock Nut Japanese Patent 2002-195236 (in Japanese)

[2]   Noda N A, Noma S, Saito K, Nagawa M, Yumoto A and Xiao Y 2006 Stress reduction effect and anti-loosening performance of outer cap nut by finite element method *Trans. the Japan Society of Mechanical Engineers* **72** 1318-25 (in Japanese)

[3]   Xiao Y, Kuhara M, Noda N A, Saito K, Nagawa M and Yumoto A 2008 Optimum dimensions of thin walled tube on the mechanical performance of super stud bolt *Trans. the Japan Society of Mechanical Engineers* **74** 954-60 (in Japanese)

[4]   Nishida S I 1997 A new method for fatigue life improvement of screws *European Structural Integrity Society* **22** 215-25

[5]   Hirai K and Uno N 2005 Fatigue strength of super high strength bolt *J. Structural Engineering* **595** 117-22

[6]   Noda N A, Xiao Y and Kuhara M 2011 The reduction of stress concentration by tapering threads *J. Solid Mechanics and Materials Engineering* **5** 397-408

[7]   Xiao Y, Wan Q, Noda N A, Akaishi Y, Takase Y and Nishida S 2011 Stress reduction effect of tapering thread bolts and nuts which have slightly different pitches *Paper Collection of Automotive Technology Society* **42** 927-33 (in Japanese)

[8]   Maruyama K 1976 Stress analysis of a bolt-nut joint by the finite element method and the copper-electroplating method *Trans. the Japan Society of Mechanical Engineers* **19** 360-8 (in Japanese)

[9]   Nippon Steel Corporation 2005 Steel Bolt Set Japanese Patent 2005-265150 (in Japanese)

[10]   Chen X, Noda N A, Akaishi Y, Sano Y and Takase Y 2013 Effect of pitch difference on anti-loosing performance and fatigue strength for high strength bolts and nuts *13th Int. Conf. on Fracture* 10988-43072

[11]   Akanishi Y, Xin C, Yang Y, Tamasaki H, Noda N A, Sano Y and Takase Y 2013 Fatigue strength analysis for bolts and nuts which have slightly different pitches considering clearance *Paper Collection of Automotive Technology Society* **4** 1111-7 (in Japanese)

[12]   Noda N A, Sano Y, Takase Y, Xin C, Maruyama H, Huan W and Fujisawa R 2015 Anti-loosing performance of special bolts and nuts having enhanced fatigue life by introducing pitch difference *Paper Collection of Automotive Technology Society* **46** 121-6 (in Japanese)

[13]   Chen X, Noda N A, Magd A W, Akaishi Y, Sano Y, Takase Y and Gusztav F 2015 Fatigue failure analysis for bolt-nut connections having slight pitch differences using experimental and finite element methods *Acta Polytechnica Hungarica* **12** 61-79

[14]   Hamanaka Nut Corporation 2006 Fastening Part and Fastening Method Japanese Patent 2006-118691