Effect of the Residual Stress on the Fatigue Strength of a Bolt in Bolt/Nut Assemblies (Verification of the hypotheses using an axi-symmetric bolt model)*

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Abstract

The residual stress at the thread root of a bolt is one of the major factors influencing the fatigue strength. Some hypotheses have been proposed to predict the fatigue strength from the local stress on the thread root. However, these have not yet been verified quantitatively since the residual stress induced by thread rolling and locally acting on the thread root can neither be measured nor estimated with sufficient accuracy. This study aims to clarify the relationship between the fatigue strength and the local stress around the thread root taking into account the effect of residual stress. For this purpose, a method is proposed where the residual stress, which can be estimated by FE analysis, is induced on the thread root of an axi-symmetrical bolt in bolt/adaptor assembly model by preloading. The results from fatigue test show that the preloaded specimen has the higher fatigue strength than non-preloaded one. This shows that the compressive residual stress could improve the fatigue strength as anticipated from Yoshimoto's hypothesis. On the other hand, the fatigue strength of a bolt calculated by FE analysis based on the local stress distribution using Ishibashi's hypothesis was smaller than that of notch-free specimen. However, experimental investigation showed that the bending stress are acting on the bolt thread root due to the construction of threaded adaptor or the fatigue test device. Finally, it can be concluded that the fatigue strength of the axi-symmetrical bolt model can be predicted by using the hypotheses taking into account the bending effect.

Key words: Fixing Element, Threaded Fastener, Bolt, Fatigue Strength, Residual Stress, Thread Root, Stress Analysis, FE Analysis, Ishibashi's Hypothesis, Yoshimoto's Hypothesis

1. Introduction

The fatigue strength of a bolt is one of the most important basic data for bolted joint design. However, it cannot be predicted with sufficient accuracy since the fatigue strength of a bolt is influenced by many kind of factors. The compressive residual stress at the bolt thread root, which is induced by thread rolling and thought to be disappeared by heat treatment (quenching and tempering), is one of the major factors influencing significantly on the fatigue strength of the bolt in bolt/nut assembly. Yoshimoto⁽¹⁾ had presented a

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hypothesis to explain the difference of the fatigue strength between the bolt thread rolled before heat-treated (called SV bolt) and thread rolled after heat-treated (called SG bolt) based on the Ishibashi's hypothesis⁽²⁾ concerning the effect of stress concentration on the fatigue strength.

Afterward, Hagiwara et al.⁽³⁾ modified Yoshimoto's hypothesis taking into account the yield property of the bolt material, and Kawai et al.⁽⁴⁾ has tried to quantify the residual stress at the groove rolled specimen by direct measurement and by estimation using 3-D FE analysis. However, the hypothesis has not yet been verified quantitatively since the accuracy of the determination of the stress locally acting on the thread root including the compressive residual stress is still insufficient.

This study aims to verify the hypotheses concerning the relationship between the fatigue strength and the local stress distribution at the thread root taking into account the effect of residual stress. Recent development in computational engineering allows us to analyze the stress induced by the fatigue loading and locally distributed at the thread root taking into account the elastic-plastic behaviors. However, the analysis is still limited to axi-symmetric model principally due to the constraint for the numbers of elements. This means that the effect of the incomplete threads of nut caused by the thread lead angle at the bearing surface, which may affect the local stress distribution, cannot be taken into consideration in the calculation. Therefore, in this study, the fatigue tests for axi-symmetric bolt model without lead angle are performed assembled with the split test adapter. For such kind of axi-symmetric test specimens (called leadless bolt hereafter), the local stress could be estimated precisely including the compressive residual stress which could be induced by preloading to leadless bolt in bolt/split adapter assembly.

2. Nomenclature

- F : Axial tensile load
- α : Stress concentration factor
- σ : Nominal stress (in general)
- σ^* : Local stress (in general)
- A_s : Stress area
- β : Fatigue notch factor
- $\sigma_{0.2}$: Strength at 0.2 % non-proportional elongation of the bolt material
- σ_T : True fracture stress of the bolt material
- σ_R : Residual stress at the thread root of bolt
- F_p : Preload inducing the residual stress at the thread root
- R_s : Stress ratio in fatigue test
- σ_{bs} : Axial stress on the bolt shank measured by strain gauge
- M : Bending moment acting on the bolt model
- I : Second moment of area of the bolt shank

3. Hypotheses on the Fatigue Strength

3.1 Ishibashi's Hypothesis

Figure 1 shows a model of the local stress distribution on the first thread root of a bolt in bolt/nut assembly.

When the axial load $F (= \sigma \cdot A_s)$ is applied to the bolt/nut assembly, the stress $\alpha \cdot \sigma$ is generated at the thread root surface by stress concentration. According to Ishibashi's hypothesis, the stress which influences on the fatigue strength is the local stress σ^* at the ε_0 inner layer from the thread root surface. This means that the fatigue notch factor β can be defined the magnitude of the stress $\sigma^* (= \beta \cdot \sigma)$.

The depth ε_0 of the layer is thought to be dependent upon the crystal grain size. It might be the order of several dozen μm and 30 μm is assumed in this study.

Fig.1 Local stress distribution on the first thread root of a bolt/nut assembly

3.2 Modified Yoshimoto's Hypothesis

Figure 2 shows the assumed relationship between the nominal stress σ and the local stress σ^* on the thread root of a bolt at ε_0 layer⁽³⁾. The red line shows the case without axial residual stress corresponding to the case with SV bolt. In the Yoshimoto's hypothesis⁽¹⁾, the bolt material was assumed to be elastic and perfectly plastic solid ($\gamma=0$), and it has been modified by Hagiwara et al.⁽³⁾ as the elastic-plastic solid with $\gamma (<\beta)$. In the case where the compressive residual stress σ_R exists at the thread root as in the case with SG bolt, it works to decrease the axial stress, and the red line is sifted to the blue one.

Figure 3 shows the fatigue limit diagram for these two cases. In this figure, all the stresses are expressed by nominal stress, and therefore the fatigue strength of a bolt is decreased by the fatigue notch factor β against the fatigue strength of the notch-free specimen shown by the straight line $\sigma_{W0} - \sigma_T$. This figure highlights that the fatigue strength of a bolt with compressive residual stress seems to be increased especially in the region where the mean stress is relatively low.

4. Estimation of the Residual Stress induced by Preloading

When the axial tensile load is applied to the leadless bolt, the microscopic plastic deformation occurs at the thread root due to the stress concentration, and the axial compressive residual stress is generated on the thread root of the leadless bolt by unloading. To estimate the residual stress induced by this preloading process, the material property in FE analysis has to be defined adequately so as to simulate the elastic-plastic behavior in

Fig.2 Assumed relationship between nominal stress and local stress on the thread root of a bolt at ε_0 inner layer⁽³⁾

Fig.3 Fatigue limit diagram of a bolt derived from modified Yoshimoto's hypothesis⁽³⁾

detail. For this purpose, a method proposed by Okubayashi et al.⁽⁵⁾ is used in which the material property is determined by using the data from tensile test for machined test piece and the corresponding FE analysis.

Figure 4 shows the FE model for the tensile test of machined test piece from the leadless bolt used in the experiment and the material property defined by using the method shown in Ref(5), respectively. The material of the leadless bolt (and machined test piece) is SCM440 and the property class is 8.8.

Figure 5 shows the load/elongation curves for the leadless bolt obtained from experiment (gray line) and FE analysis (red line) using the FE model based on measured dimensions shown in Table 1 and material property shown in Fig. 4(b). From Fig. 5, it is clarified that the calculated result shows good agreement with the experimental one, and that no macroscopic plastic deformation occurs in the bolt if the axial tensile load is less than 40 kN. Considering this, the preload F_p applied was determined to be 35 kN to induce the compressive axial residual stress at the thread root of the leadless bolt.

Figure 6 shows the axial residual stress distributions at the first thread root of a bolt obtained by FE analysis for $F_p = 35$ kN for two types of the adapter in which only the thicknesses of the first internal thread mated with bolt thread are different ($1/4P$ or $1P$). The results show that the magnitude of the compressive residual stress at the ε_0 layer is affected by the thickness of the first internal thread of the adapter. On the other hand, in the practical bolt/nut assemblies the thickness of the first internal thread continuously changes from 0 to

Fig.4 FE model for tensile test of machined test piece and material property obtained

Table 1 Dimensions of FE model

Bolt model		Adapter model	
Major diameter d	9.86 mm	Minor diameter D_1	8.78 mm
Pith diameter d_2	9.07 mm	Pith diameter D_2	9.27 mm
Minor diameter d_3	8.34 mm	Pitch of thread P	1.249 mm
Root radius r	0.18 mm	Coefficient of friction between threads μ_{th}	0.2
Pitch of thread P	1.247 mm

Fig.5 Load/elongation curves for leadless bolt specimen derived from experiment and FE analysis

Fig. 6 The effect of the thickness of the first internal thread on the axial residual stress at the first thread root of a bolt calculated by FE analysis ($F_p = 35$ kN)

1P (full thread) due to the lead angle. This is the major reason why we use the leadless bolt also in the experiment instead of bolt with lead angle.

Figure 7 shows the residual stress distributions on 1st to 7th thread roots induced by the preload of $F_p = 35$ kN. The compressive residual stress is the greatest at the 1st thread root

Fig. 7 Axial residual stress distributions on 1st to 7th thread roots of a bolt calculated by FE analysis ($F_p = 35$ kN, $1P$ -type adapter)

surface, and it decreases rapidly in the inner layer of $\zeta \geq 0.1$ mm. At the ε_0 layer, the magnitude of the maximum compressive residual stress is about 675 MPa for the $1P$ -type adapter. On the other hand, the residual stress of SG bolts estimated by calculation based on the modified Yoshimoto's hypothesis⁽³⁾ from the fatigue test results⁽⁶⁾ for the SV and SG bolts in bolt/nut assembly is about 1200 MPa. However, the compressive residual stress of 675 MPa is expected to increase the fatigue strength of the leadless bolt in bolt/adapter assembly by 35% in the low mean stress condition.

5. Fatigue Test

5.1 Test procedure

M10×1.25 leadless bolt specimens have the same thread profile as M10×1.25 bolt except the thread lead angle. The result of X-ray stress measurement for groove-rolled specimen made of the same material and heat-treated in a same batch as in this study⁽⁷⁾ shows that the residual stress induced by thread rolling disappears completely by the following heat treatment (quenching and tempering).

Figure 8 shows the schematic drawing of the $1P$ -type split adapter used for the fatigue test. This adapter has external thread (M20×1.5) to fix to the fatigue testing device, and is split into two pieces by wire cutting.

Figure 9 and Table 2 show the fatigue testing device and the conditions, respectively. Fatigue tests in the condition of low mean stress ($R_s = 0.1$) where the effect of the residual stress is thought to be significant were performed for the preloaded and non-preloaded leadless bolts.

Fig. 8 $1P$ -type split adapter

Fig. 9 Setup of fatigue test

Table 2 Fatigue test conditions

No.	Preload F_p	Fatigue loading
1	0 kN	Stress ratio
2	35 kN	$R_s = \frac{F_{\min}}{F_{\max}} = 0.1$

5.2 Test Results

Figure 10 shows the experimental results obtained from staircase fatigue tests. This results show that the fatigue limit (fatigue strength : σ_{AN} , $N=5 \times 10^6$) of the preloaded leadless bolt is 20 % higher than that of non-preloaded one.

Figure 11 shows the comparison between the fatigue strength of leadless bolts and that of notch-free specimen by using the local stress σ^* at the layer of $\varepsilon_0 = 30 \mu\text{m}$. The procedures to obtain the fatigue limit described by the local stress is as follows:

1. Calculate the maximum and minimum loads corresponding to each fatigue limit as,

$$\begin{cases} F_{\max} = (\sigma_m + \sigma_{AN}) \cdot A_s = \left(\frac{1+R_s}{1-R_s} + 1 \right) \sigma_{AN} \cdot A_s \\ F_{\min} = R_s \cdot F_{\max} = 0.1 F_{\max} \end{cases} \quad (1)$$

2. Calculate the local stresses $\sigma_{\max}^*$ and $\sigma_{\min}^*$ at the ε_0 layer by FE analysis.
3. Calculate the local stress σ_a^* and σ_m^* as,

$$\begin{cases} \sigma_a^* = \frac{\sigma_{\max}^* - \sigma_{\min}^*}{2} \\ \sigma_m^* = \frac{\sigma_{\max}^* + \sigma_{\min}^*}{2} \end{cases} \quad (2)$$

Fatigue strength of notch-free specimen was drawn by the estimated fluctuating fatigue strength $\sigma_{W0}^{(8), (9)}$ and the true fracture strength σ_T measured. This figure shows that the fatigue strengths of leadless bolts calculated by FE analysis are about 50 % smaller than that of notch-free specimen although the effect of the mean stress of the fatigue loading, i.e., the gradient of the diagram shows almost the same tendency as the fatigue strength diagram for the notch-free specimen.

5.3 Considerations

To clarify the reason why the fatigue strength of the leadless bolt in bolt/split adapter assembly described by the local stress is smaller than that of notch-free specimen, the axial stress acting on the leadless bolt was measured by a couple of strain gauges, put on the bolt shank.

Figure 12 shows the relationship between the tensile load and the axial stress measured on the bolt shank. This figure shows that the maximum bending stress is generated by the tensile loading to the perpendicular to the split of the threaded adapter [case a) in Fig.12], which might be caused by the shearing action between split parts of the adapter due to the slippage at the outer mating threads. This may affect to decrease the apparent fatigue strength of the leadless bolt by increasing the local stress.

Assuming that the fatigue notch factor β is constant also when the bending moment is acting, the modified local stress σ^{**} at the ε_0 layer of the thread root can be calculated as,

$$\sigma^{**} = \sigma^* + \beta \cdot \frac{M}{I} \cdot \frac{d_3}{2} \quad (3)$$

Fig. 10 Experimental results from staircase fatigue tests

Fig. 11 Comparison of the fatigue strength of leadless bolts in bolt/split adapter assemblies and that of notch-free specimen based on the local stress σ^*

Fig. 12 Relationship between the tensile load and the measured stress on the bolt shank

Table 3 Calculated local stress σ^* , local bending stress σ_b^* and modified local stress σ^{**}

Preload F_p kN	Calculated local stress MPa		Local bending stress MPa		Modified local stress MPa	
	$\sigma_{\min}^*$	$\sigma_{\max}^*$	$\sigma_{b\min}^*$	$\sigma_{b\max}^*$	$\sigma_{\min}^{**}$	$\sigma_{\max}^{**}$
0	31	355	104	349	135	704
35	-177	208	125	346	-52	554

Table 3 shows the calculated results from FE analysis and equation (3). The fatigue notch factor β ($=2.1$) is defined from estimated relationship between the local stress at $\varepsilon_0=30\ \mu\text{m}$ layer at the thread root and the nominal stress of the leadless bolt obtained by FE analysis.

Considering this bending effect, both of the local stresses at the fatigue limits increase to the plots marked $\blacktriangle$ and $\blacktriangleleft$ in Fig.11, and they coincide with the fatigue strength of the notch-free specimen.

6. Conclusions

The main conclusions obtained in this study are summarized follows:

- (1) Fatigue test for the leadless bolt in bolt/split adapter assembly is performed to exclude the effect of the thread lead angle on the rigidity of first internal thread.
- (2) Fatigue strength of preloaded leadless bolt is increased by the compressive axial residual stress at the thread root induced by preloading.
- (3) The fatigue strength of the leadless bolt can be predicted from the fatigue strength of notch-free specimen by using the hypotheses taking into account the bending effect.

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