PLASTIC-REGION TIGHTENING OF BOLTS CONTROLLED BY ACOUSTIC EMISSION METHOD

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Abstract

We have proposed a control method for plastic-region tightening of bolts using AE method. In this paper, in order to investigate the validity of the tightening control by AE method, the tightening test in simulated factory environment was conducted and both tightening accuracy and variations were compared with those by conventional control methods. The results show that AE method is more effective for plastic-region bolt tightening control than the conventional methods. Finally, a new system using a Maharanobis distance for controlling plastic-region bolt tightening by AE method was developed.

Keywords: Plastic-region bolt tightening, tightening control, Maharanobis distance

Introduction

A plastic-region tightening method used in the automotive industries is known as a good method for preventing fatigue of bolts. However, the most common tightening-control method by using a torque wrench (called torque-control bolt tightening method) cannot apply to a plastic-region tightening [1]. Both an angle control method and a torque-gradient control method are regulated in JIS (Japanese Industrial Standards) [2] for a plastic-region tightening control, although the method requires a special torque wrench and complicated procedures. We have proposed a new control scheme using AE method, but the accuracy and validity were not examined. In this paper, in order to investigate the accuracy and validity of the tightening-control in field, the tightening test was conducted. The tightening-accuracy and variation by AE method were found superior to those controlled by conventional methods.

Experimental Setup and Method

When a tightening is performed in field, noise due to friction on bearing surfaces was monitored with AE. In order to confirm whether AE method can be utilized in an industrial condition, tightening test in simulated factory environment was performed. Moreover, accuracy and variation of the tightening control by AE method were compared to those by conventional methods (angle control method and torque-gradient control method). Figure 1 shows photograph and schematic illustration of experimental setup used for the test. The axial load of a bolt was measured by a load cell (TEAC, TU-NR-C50kN), which was placed between two steel plates (SKS93, thickness: 10 mm). We prepared two sets of steel plates, of which surface roughness (arithmetical mean surface roughness) were less than 3.1 µm (plate 1) and 25 µm (plate 2). A torque was measured with a digital torque wrench (Nakamura, DTC-N1000EX). A potentiometer (Nidec Copal Electronics Corp., M-22E10-050 1k) was used for measuring the rotation angle. A socket of a torque wrench was equipped with a timing pulley, rotation angle of a bolt was transmitted to the potentiometer with the timing belt, and the rotation angle was measured. An AE sensor (PAC, Type: PICO) was attached to a bolt head.
AE signals were filtered by high-pass filter of 100 kHz and amplified 66 dB by AE analyzer (NF Electronic instruments, Type: 9501). By using this experimental setup, a torque, an axial load, a rotation angle and AE can be measured simultaneously during bolt tightening.

![Photograph and schematic illustration of tightening test.](image)

Fig. 1 Photograph and schematic illustration of tightening test.

**Conventional Control Methods**

We first investigated tightening accuracy and variation of conventional methods. One of the plastic-region tightening control methods regulated in JIS B 1083 is an angle control method. According to the JIS, desired angle ($\theta_{fA}$) for a plastic-region tightening is determined by a following equation.

$$\theta_{fy} \leq \theta_{fA} \leq \frac{1}{2} \left( \theta_{fy} + \theta_{fu} \right)$$

(1)

Here, $\theta_{fy}$ is rotation angle corresponding to the yield point of bolts, and $\theta_{fu}$ is that of the ultimate point. Angles of $\theta_{fy}$ and $\theta_{fu}$ are determined by load-rotation angle diagram as shown in Fig. 2. Desired angle-range for plastic-region tightening (Eq. (1)) and axial-load-range controlled by the method are shown in the figure as $\Delta \theta_f$ and $\Delta F_f$, respectively.

Next, we conducted several experiments and the accuracy and variation of tightening control were examined. Since the axial loads of yield point and ultimate point varied with torque applied to bolts and the applied torque is changed by tightening conditions (even if bolts with same lot are used), it is needed to normalize axial load when the data of different experiments are compared. The following normalized axial-load $F^*$ is introduced for this purpose:
Here, $F_{f_{\text{amin}}}$ and $F_{f_{\text{amax}}}$ are axial loads correspond to minimum and maximum of desired angles by Eq. (1). $F_{fu}$ and $F_{fy}$ are the yield load and ultimate load determined by $\theta_{f}$-$F_f$ diagram for every experiment. Therefore, when a symbol $F^*$ becomes 0, axial load of bolt reaches the yield point, and when a symbol $F^*$ becomes 1, axial load reaches the ultimate point. Results of 8 experiments (1-5th experiments used plate 1, 6-8th experiments used plate 2) are shown in Fig. 3. When a desired tightening angle is set to a minimum in the range defined by the Eq. (1), the variation of axial loads for every examination becomes large, although, while a desired angle is set to a maximum, the variation becomes small and axial-loads are controlled at near the ultimate load. Axial tensions of each examination are always set in the range of 0 to 1, and it can be said that the angle control method is an accurate control method for plastic-region tightening. The other plastic-region tightening control method regulated in JIS B 1083 is a torque gradient control method. According to the JIS, desired torque gradient ($dT_f/d\theta_f$) for a plastic-region tightening is determined by the following equation:

$$\frac{1}{3} \left( \frac{dT_f}{d\theta_f} \right)_{\text{max}} \leq \left( \frac{dT_f}{d\theta_f} \right) \leq \frac{1}{2} \left( \frac{dT_f}{d\theta_f} \right)_{\text{max}}$$

(3)

Torque, torque gradient and axial tension with tightening angle monitored during 1st experiment are shown in Fig. 4. Desired range for plastic-region tightening (Eq. (3)) and axial-load range controlled by the method are also shown. In order to discuss tightening control accuracy for each experiment and variation for every experiment, the normalized axial load of eight experiments are investigated (see Fig. 5). Tightening variations were large compared to
Fig. 3 Accuracy and variations of axial load.

those by angle-control method (Fig. 3). Furthermore, the result shows that there is a possibility that the axial load will not be managed in a plastic region in some cases. Therefore, this control method is inaccurate.

Fig. 4 Tightening range of torque-gradient method.
Acoustic Emission Method

Variations of AE event count rates and Ib-values with tightening angle during tightening is shown in Fig. 6. Axial tension vs. tightening angle diagram is also shown.

Fig. 6 AE activities during bolt tightening.
We observed a large number of AE events in the initial stage of the test. These AE signals are noise due to friction on the bearing surfaces. In spite of having measured many noise events, this result clearly shows that AE event count rates have a peak near the yield point and \( I_b \)-values reach the peak just beyond the yield point. Therefore, AE signals due to plastic deformation can be monitored even in real tightening conditions as the indicator of yielding. Both AE event count rates and \( I_b \)-values will be useful parameters for controlling plastic-region tightening. Figure 7 shows normalized axial load controlled by AE method for eight experiments. Maximum position in each experiment is determined by the peak in \( I_b \)-values, and the minimum position by the AE event count rate peak. Variations for the experiments are similar to that of angle control method (when desired angle is set to the maximum value in Eq. (1)). The axial loads of experiments were controlled in the range of 0.2 to 0.7, and the average variation was \( \pm 0.11 \). This compares favorably with \( \pm 0.16 \) and \( \pm 0.30 \) for angle control and torque-gradient control methods, respectively. This demonstrates that AE method is the most accurate control method for plastic-region tightening among the three examined here. Although roughness of the bearing surfaces differs between the 1\(^{\text{st}}\)-5\(^{\text{th}}\) experiments and the 6\(^{\text{th}}\)-8\(^{\text{th}}\) experiments, AE method has controlled the axial load appropriately. The experimental results show that AE method is more effective in plastic-region bolt tightening control than the conventional methods.

**Development of Plastic-region Bolt Tightening Control System**

In the previous section, we showed a feasibility of controlling plastic-region tightening by AE method. However, it is difficult to judge the peak of AE parameters due to plastic deformation automatically by a computer system. Thus, we developed a method in lieu of the peak detection of AE event count rates and \( I_b \)-values. The new method relies on the Maharanobis distance and a new index for judgment is defined; i.e., the inverse of Maharanobis distance.

Here, Maharanobis distance of AE signals detected is defined as follows [3, 4]:

![Fig. 7 Accuracy and variations of axial load.](image)
\[ D = \frac{\sqrt{((x - \bar{x})/\sigma)^T \cdot R^{-1} \cdot ((x - \bar{x})/\sigma)}}{p} \]  

(4)

Here, \( x = [x_{\text{ref}}, x_{\text{th}}] \) is a two-dimensional vector consisting of the AE event count rate and the Ib value of the comparison data. \( \bar{x} = [\bar{x}_{\text{ref}}, \bar{x}_{\text{th}}] \) is a two-dimensional vector, consisting of the averages of the reference AE parameters. We used the event count rate and the Ib-value that were detected at a yielding range of \( \theta = 164^\circ-180^\circ \) in the 1st experiment for the angle-control method as the reference AE parameters. \( p \) is the number of the dimension and is two for this study. \( R^{-1} \) is an inverse matrix of a sample correlation matrix.

The inverse of Mahalanobis distance during 4\(^{th}\) and 6\(^{th}\) experiment is shown in Fig. 8. The axial load-tightening angle diagram is also shown. The inverse of Mahalanobis distance became large when the axial load reaches the yield point. This can be used to judge the yield point during tightening. Note that the conditions for 6\(^{th}\) experiment tightening are not the same as those for the reference data (plate No. 2 was used); thus the absolute value of the inverse of the Mahalanobis distance is smaller than that of 4\(^{th}\) experiment.

Based on the experimental results, the judging criteria of the plastic-region tightening was determined as follows;

1) The torque become larger than 20 [N·m].
2) Inverse of Maharanobis distance become larger than 5.

![Graph showing axial load, torque, and inverse of Mahalanobis distance over time](image)

**Fig. 8 Inverse of Maharanobis distance during the test**

(left: 4\(^{th}\) experiment, right: 6\(^{th}\) experiment).

We developed a control system for plastic-region tightening as shown in Fig. 9. The equipment consists of a digital torque wrench, an AE monitoring device, and an analysis system. AE sensor was attached to the head of a bolt. AE parameters and torque were monitored and analyzed by the developed software. When correct tightening conditions are reached, the LED in the software-screen is turn on. Figure 10 shows the axial load, torque and inverse of Mahalanobis distance when tightening is conducted by the developed system. As we used plates in which the surface roughness was not regulated, tightening conditions differed from those of the
reference data. The absolute values of the inverse of the Mahalanobis distances were smaller than those of Fig. 8. Although ratchet mechanism of wrench was used during tightening, appropriate judging was performed by the developed system.

![Diagram of control system](image)

**Fig. 9** Developed control system for plastic-region tightening.

**Conclusion**

Fundamental study of plastic-region bolt-tightening control by AE method was conducted. Results are summarized as follow:

1) Tightening test in simulated factory environment was conducted and both the accuracy and variations of tightening were compared with those by conventional control methods. It was found that AE method is superior to conventional methods for plastic-region bolt-tightening control.

2) A new control system for plastic-region bolt tightening was developed. A new index for judging the yield point was implemented in the analysis system. The utility of the developed system was demonstrated by conducting tightening tests successfully.

**References**


Fig. 10 Axial tension, torque and inverse of Maharanobis distance during the test.