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PROPOSAL OF EVALUATION METHOD FOR RESIDUAL AXIAL FORCE OF CORRODED HIGH-STRENGTH BOLTS

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In this research an evaluation method for the residual axial force of corroded high-strength bolts was investigated. Corroded high-strength bolts cut from a steel bridge were used for the measurement of thickness reduction and residual axial force. For the residual axial force measurement, a strain-gauge method with a core extraction was applied. An FE analysis examined the effect of the corroded shape of high-strength bolts on the residual axial force. The results reveal that the effect of corroded shapes on the residual axial force can be considered by using the thickness reduction amount near the washer for nut and bolt head. A proposed evaluation method based on the summation of thickness reduction can estimate the residual axial force of corroded high-strength bolts approximately.

Keywords: FE analysis, Fastener corrosion, Thickness reduction, Corrosion damage.

1 INTRODUCTION

Recently, steel bridges constructed during Japan's rapid economic growth are under repair or closed to traffic due to corrosion damage. Since corroded steel bridges will increase drastically in a few decades, appropriate maintenance methods for corrosion damage are necessary. High-strength bolts of friction joints are one of the parts most affected by corrosion. It has been reported that the residual axial force of high-strength bolts is reduced with a decrease in bolt thickness. Since the loading capacity of friction joints depends on the residual axial force, it is important to evaluate the residual axial force of corroded high-strength bolts. This is investigated by this research.

2 THICKNESS REDUCTION OF CORRODED HIGH-STRENGTH BOLTS

The specimens shown in Fig. 1 were cut from a steel bridge. The thickness reduction was measured with a slide gauge, a square ruler, and a taper gauge. For the nuts, the measurement points were at a height of 0, 4, 8, 12, 16, and 20mm from the washer. In the case of bolt heads, the points were 0, 4, 8mm, and the top surface. Fig. 2 shows an example of the results. The vertical axis is the height from the washer, and the horizontal axis indicates the residual thickness. The corroded shape was approximately obtained. Based on the results, both average thickness reductions of nut $\delta_{N\_ave.}$ and bolt head $\delta_{H\_ave.}$ shown in Fig. 3 were calculated by the following equations:

$$\delta_{\mathrm{N\_ave.}} = W - B = 2 \times \frac{\sum_1^6 \delta_{Ni\_ave.}}{6} \tag{1}$$

$$\delta_{\mathrm{H\_ave.}} = U - A = 2 \times \frac{\sum_1^6 \delta_{Hi\_ave.}}{6} \tag{2}$$

where $\delta_{\mathrm{N}i\_ave.}$ is the average thickness reduction amount at the nut side i, and $\delta_{\mathrm{H}i\_ave.}$ is the average thickness reduction amount at the bolt head side i.

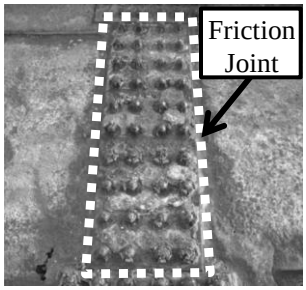


Figure 1. Specimen cut from a steel bridge.

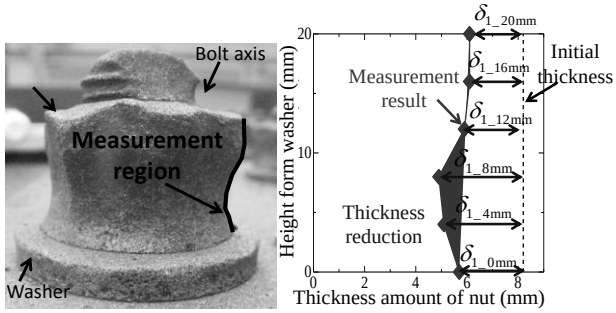
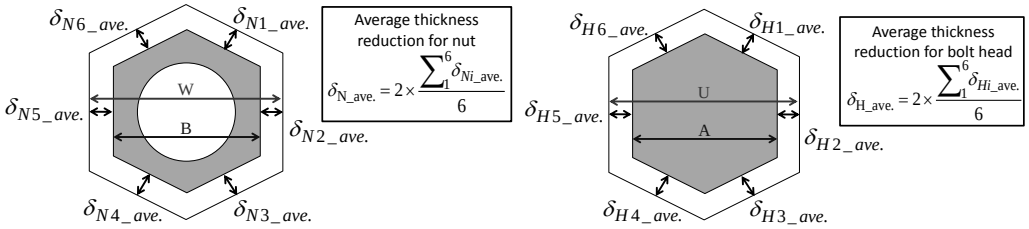


Figure 2. Example of measurement results of bolt shape.



(a) Nut. (b) Bolt head.

Figure 3. Definition of average thickness reduction.

3 MEASUREMENT OF RESIDUAL AXIAL FORCE

The residual axial force was measured with the actual high-strength bolts. For the residual axial force measurement, the strain gauge method with a core extraction, which was modified to consider the reduction effect of bolt head height, was applied. By using the average thickness reduction, the relationship between the thickness reduction amount and the residual axial force were examined.

3.1 Measurement Results of Residual Axial Force

The strain gauge method for the residual axial force of high-strength bolts measures the strain value at the bolt head surface during the axial force releasing, and then estimates the residual axial force by this strain value. However, it was too difficult to release the axial force of corroded high-strength bolts due to the thickness reduction. As shown in Fig. 4, therefore, a core extraction was applied in order to release the axial force. From

the previous research (Shimozato *et al.* 2013), this method could obtain a high accuracy of 98% in the case of new high-strength bolts.

The measurement results are shown in Fig. 5. The horizontal axis indicates the summation of thickness reduction amounts of nut and bolt head, and the vertical axis shows the percentage of residual axial force, calculated by dividing by the measured axial force by the design one. Some of the results were more than 100%. Since there is no way to increase the axial force, it should represent the effect of corrosion at the bolt head on the measurement strain.

Figure 4. Strain gauge method with core extraction for measurement of residual axial force.

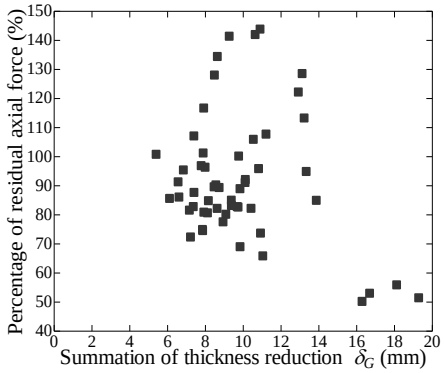


Figure 5. Relationship between residual axial force and thickness reduction.

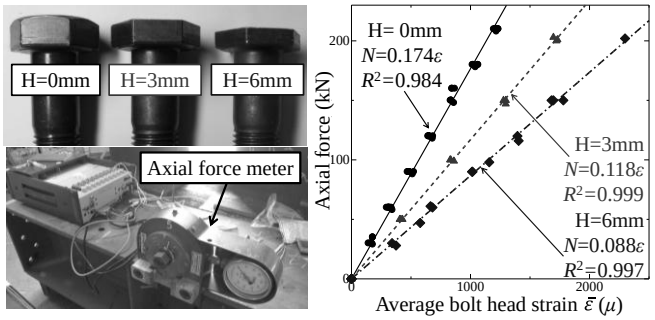
3.2 Effect of Bolt Head Height Reduction on Residual Axial Force Measurement

To investigate the reduction effect of bolt head height on the measurement strain, the relationship between the release strain and the axial force was investigated using the high-strength bolts with different bolt head heights. The cases of height reduction H were 0, 3, and 6mm, as shown in Fig. 6(a). The test results were indicated in Fig. 6(b). The ordinate is the introduced axial force and the abscissa is the bolt head strain. It is obvious that the slopes of regression lines decrease with increase in the reduction of bolt head height. Based on these results, the following equation was obtained:

$$\begin{aligned} N &= S\bar{\varepsilon} \\ &= \left(0.0014H^2 - 0.023H + 0.174\right)\bar{\varepsilon} \end{aligned} \tag{1}$$

where N is the residual axial force (kN), H is the reduction of bolt head height (mm) and $\bar{\varepsilon}$ is the released strain at the bolt head.

The reevaluated results of Fig. 5 are shown in Fig. 7. As shown in the figure, most of measured axial force percentage was less than 100%. In addition, the residual axial force tends to decrease with an increase in the summation of both thickness reduction amounts. Hence, it seems to be valid to evaluate the residual axial force by using the summation of thickness reduction amounts. However, the correlation factor of regression line drawn in the figure was 0.49, i.e., the correlativity was not so high. The cause should be the corroded shape effect of high-strength bolts.



(a) Specimen and test situation. (b) Measurement result.

Figure 6. Relationship between axial force and bolt head strain with different bolt head height.

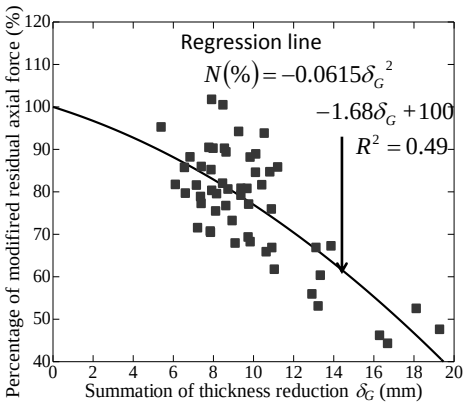


Figure 7. Relationship between residual axial force and thickness reduction.

4 EVALUATION METHOD FOR RESIDUAL AXIAL FORCE

4.1 Effect of Corroded Shape on Residual Axial Force

The corroded shapes of high-strength bolts are divided into 4 types, such as box, hourglass, trapezoid and inverted trapezoid, as shown in Fig. 8. In this chapter, the effect of corroded shapes on the residual axial force was investigated by FE analysis.

FE analysis used the analysis model in Fig. 9. Considering the symmetry, a 1/6 model was created. Elastic modulus was 210GPa, Poisson's ratio was 0.3. Yield strengths were 900MPa for the bolt and washer and 245MPa for both base and splice plates, respectively. Perfect elasto-plasticity was applied for the constitutive law. The boundary condition was indicated in Fig. 10. The contact was defined between each member. Average thickness reductions of each shape type were 6, 8, and 10mm. The analysis results were shown in Fig. 11. The vertical axis is the percentage of axial force, and the horizontal one is the average thickness reduction. As indicated in the figure, even if the average thickness reduction was same, the residual axial forces of each shape type were different. Therefore, it is obvious that the corroded shape has the effect on the residual axial force.

4.2 Proposal of Evaluation Method for Residual Axial Force

To examine the effect of bolt shapes on the residual axial force, the contact forces of each screw thread were obtained from analysis results. Fig. 12 shows the percentage of contact force of each thread in the total contact force. From the figure, clearly most of the total contact force was transmitted by the threads until the fifth thread.

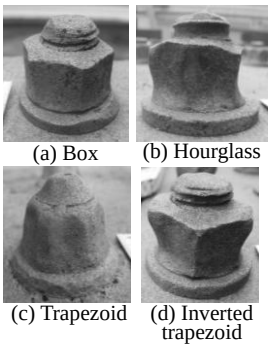


Figure 8. Examples of corroded bolt shape.

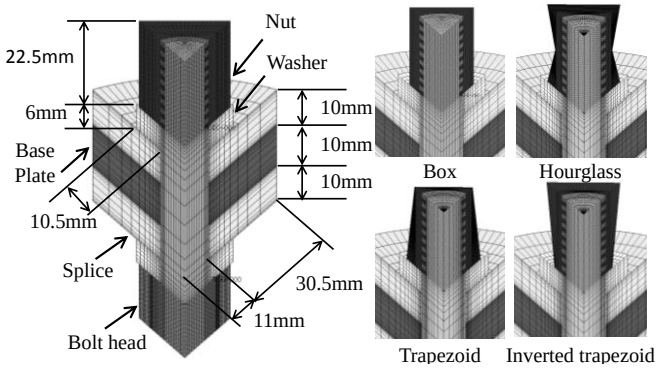


Figure 10. Boundary conditions.

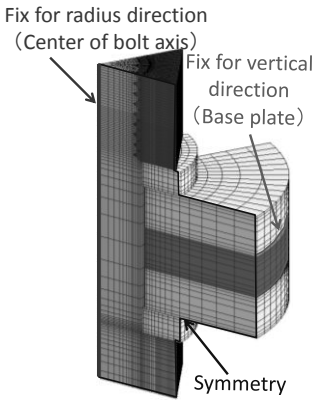


Figure 9. Analysis model.

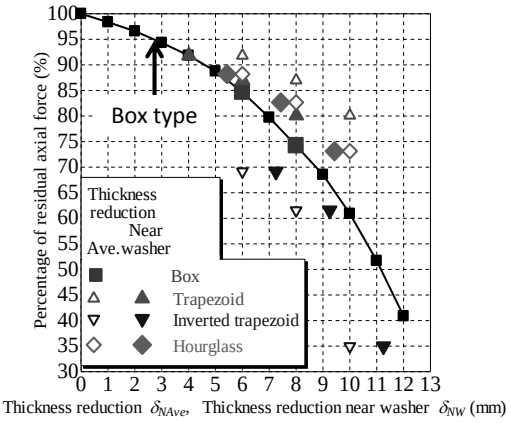


Figure 11. Analysis results.

The analysis results shown in Fig. 11 were reevaluated with a thickness reduction near the washer, defined as the average thickness reduction at the height between No.1 and No.5 threads. Reevaluated results are in Fig. 11. Since the reevaluated results become closer to the box-type results, applying thickness reduction near the washer allows the effect of bolt shape on the residual axial force to be evaluated approximately.

The test results indicated in Fig. 7 were evaluated by the thickness reduction near the washer. Fig. 13 shows reevaluated test results. Vertical axis is the percentage of modified residual axial force, and horizontal sums both thickness reductions near the washer. As shown, the correlativity of regression line increases compared with Fig. 7.

Hence, it is valid to use the summation of thickness reduction near the washer to evaluate the residual axial force of corroded high-strength bolts. Also, by considering twice of the standard error, the residual axial force can be estimated conservatively.

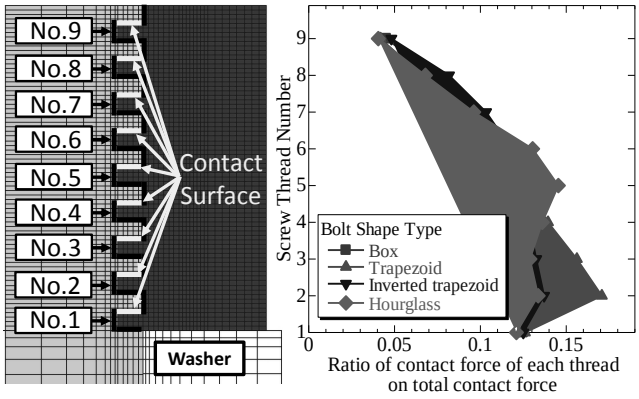


Figure 12. Ratio of contact force of each screw thread.

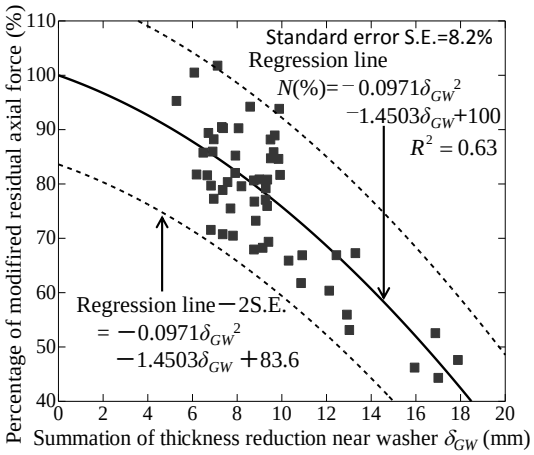


Figure 13. Reevaluated test results of residual axial force and thickness reduction near washer.

5 CONCLUSIONS

- Most of the axial force is transmitted by the threads until the fifth thread.
- Corroded shapes can be evaluated using the thickness reduction near the washer.
- The summation of both thickness reductions near the washer of nut and bolt head can approximate the residual axial force of corroded high-strength bolts.

Reference

Shimozato, T., Tai, M., Arizumi, Y., Yabuki, T. and Nagamine, Y., A study on evaluation for residual axial force of corroded high-strength bolts, *Journal of Structural Engineering*, JSCE, Vol.59A, 725-735, March, 2013.