Axial Force Behaviors of High-strength Bolt Treated by High Power CW Leaser

Qidi Wang[1], Shigenobu Kainuma[1], Shusen Zhuang[1], and Peng Huo[2]
[1] Department of Civil Engineering, Kyushu University, Fukuoka, Japan
[2] CoolLaser Division, TOYOKOH Inc., Shizuoka, Japan
Email: wang-qd@doc.kyushu-u.ac.jp, kai@doc.kyushu-u.ac.jp, zhuang-ss@doc.kyushu-u.ac.jp and hou.kaku@toyokoh.com

***Abstract*— In this study, the axial force loss of high-strength bolt after 3kW CW-laser treatment was examined. High-strength bolt specimens were prepared, and a hand-held laser transmitter was irradiated on the bolt head with CW-laser power of 3kW. The change in the axial force on the bolts was examined during the bolt's treatment based on the irradiate duration on the bolt surface. Axial force loss of the bolts was affected by the irradiation duration and position. With multiple irradiations on the bolt head, the axial force loss reduced compared with the same irradiation time was confirmed. From the relationship between the axial force change and the treatment duration, axial force loss equations of bolt side laser treatment were suggested based on multiple round irradiations, which can help estimate the axial force loss and make the maintenance plan.**

***Index Terms*—high strength bolt, Axial force loss, CW-Laser treatment, corrosion maintenance**

I. Introduction

Corrosion is the primary cause of the deterioration of steel structures which is widely concerned by engineers. The steel plate and beams have already mature surface cleaning and maintenance, but as one of the basic connection forms, bolts are still lacking in the research of surface treatment methods to protect from corrosion problems [1]. Most of the bolts in existing structures are ordinary high-strength bolt coated for corrosion protection. Some of the bolts' head is hexagonal and the coating on the corner parts is usually thinner than the other parts, and the structure of the bolt joints is usually complicated [2, 3]. The deposited rainwater and pollutants also aggravate the corrosion. According to the experimental study of high-strength bolts considered corrosion damage on bolt's head [4–6], the corrosion damage of the bolt head is the main reason for the decrease of the bolt axial force. It has also influenced the corrosion of the steel plates of the bolt joints, which may accelerate the failure of the structure.

To avoid the failure of bolt joints caused by corrosion, use a continuous-wave laser (CW-Laser) to perform surface treatment on the early corroded high-strength bolts. Previous studies [7] confirmed that continuous laser treatment can obtain a clean surface, and the laser can be irradiated to parts that other surface treatment methods cannot reach through reflection. However, laser surface treatment cannot avoid considering the effect of temperature on the structure. CW-laser irradiation of the surface usually reaches a high temperature of 1000℃ [7], and it may cause deformation and creep on the washers, resulting in the loss of bolt axial force [8].

This study uses a 3kW CW-laser to manually irradiate the bolt head and consider the impact of different irradiation durations on the bolt axial force loss. The results can provide a reference for the future laser treatment of early corroded bolt joints.

II. Test Method

To obtain the change in the axial force of the bolts to examine the relationship between the axial force loss and the laser irradiation, the F10T high-strength bolt with a 22mm diameter(M22) and a friction connection specimen were selected, as shown in Fig.1 (a) and (b). To easily facilitate transportation and laser irradiation, the specimens were cut in half before the sample was assembled.

The steel plates of the specimens were treated with steel slag abrasive blasting before assembly. The blasting distance was 300mm, with an angle of 60°, and the spray pressure of 0.7MPa. All bolts were wiped with clean oil before assembly to avoid the loss of axial force caused by friction [9]. The specimens were assembled at a room temperature of 25℃, and all bolts were tightened with the electric torque wrench. Laser treatment was performed in the factory a week after the specimens were assembled. The environment temperature during processing was about 30℃. The treatment was carried out using the CW-Laser rotated by a prism as a spinning 3kW laser ring. The basic parameters of the laser were listed in Table I, irradiating the steel surface with the ring moving to remove corrosion products and contaminants on the surface. The hand-held laser transmitter was used to irradiate the specimens. The distance between the transmitter and the irradiated surface was about 210mm. The laser ring rotated clockwise around the bolt head during the irradiation, with every 20s as an irradiation duration unit. After irradiation, the specimen cools down

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in the in-door environment to 35℃ and finishes the data counting. During the entire irradiation process, the axial force and the temperature change of the bolt were recorded through the datalogger (TDS-530, Tokyo Measuring Instruments Lab, Japan).

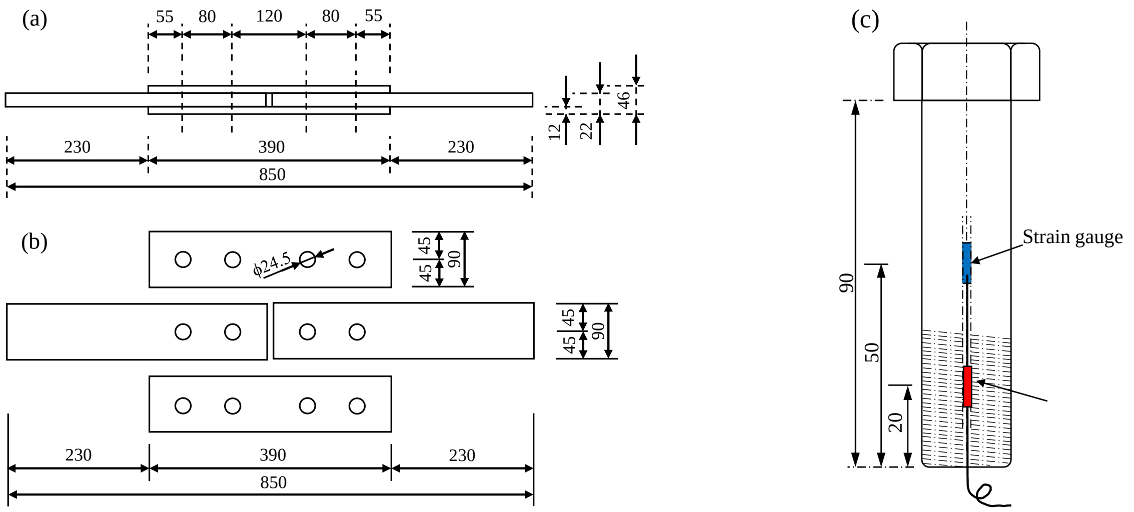

Figure 1. Dimensions of the friction connection specimen of (a)front view and (b)plane view and (c)the high-strength bolt with strain gage (unit: mm)

TABLE I. LASER PROCESSING PARAMETERS

Parameter	Value	Unit
Output	3	kW
Spot diameter	430	μm
Motor speed	5000	rpm
Irradiation ring diameter	26	mm

III. TEST RESULT AND DISCUSSION

The axial force of the bolt was obtained by measuring the value change of the strain gauge embedded in the bolt. As shown in Table.2, was the initial strain and corresponding axial force of the tested bolts, listed the initial strain (ε), strain, and axial force after tightening in the lab (ε_{Lab} and F_{Lab}) and after early loss (ε_0 and F_0), the ratio of axial force to the standard axial force (F%) and the axial force loss ratio (Δ%). In the week between assembly and laser treatment, the axial force of each bolt decreased slightly with the Δ% less than 1%. Since the axial force of each bolt cannot be exactly the same when the bolt was tightened and after the initial loss of stress, so that defines the ratio of the real-time axial force F_t to the axial force after early loss F_0 as the axial force change F_t/F_0 used for analysis. In addition, because the local temperature in the room changes significantly during the laser treatment and the thermal elongation of the strain gauge changes linearly with temperature, the measured temperature value is analyzed by the temperature change ΔT.

Considering the different corrosion levels of the bolt surface, we carried out two different treatment durations of the 20s and 80s for comparison when analyzing the influence of laser irradiated on the bolt head. Fig.2(a) shows the F_t/F_0 and ΔT change during laser irradiation. From the F_t/F_0 - t and ΔT -t curve during the laser irradiation, the changes of axial force were summarized in 4 stages: 1) The bolt's axial force increases to the maximum F_{max} during laser irradiation; 2) The axial force drops to the minimum F_{min} after the laser irradiation stop; 3) The axial force is restored during the bolt cooling down; 4) The axial force is stable to F_s after cooling down.

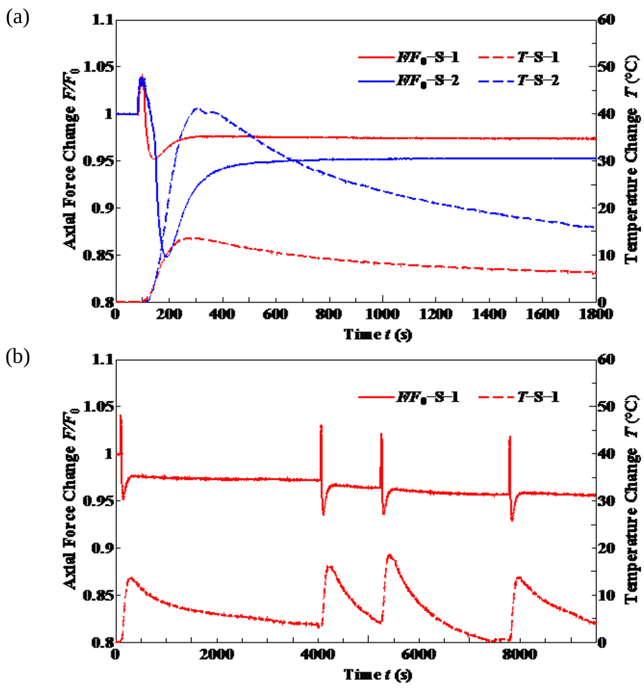

Figure 2. F/F_0 - t curve and ΔT -t curve of specimens irradiated on the bolt head, (a) single irradiation and (b) multiple irradiations

TABLE II. INITIAL STRAIN AND AXIAL FORCE OF MEASURED BOLTS

Specimen	ε	ε_{Lab}	F_{Lab} (kN)	F%	ε_0	F_0 (kN)	F%	Δ%
S-1	1435	4736	226	110%	4734	226	110%	0.1%
S-2	2036	5559	223	109%	5528	221	108%	0.9%

The rapid increases of the axial force in the first stage were caused by the vast amount of heat energy input to the bolt head during the laser treatment. The surface temperature can reach 1000℃ in an instant [7], causing the thermal expansion of the bolt head and washer[10, 11]. This stage occurs within the first 20s. During this stage, all of the bolt axial force increased by about 5%. After a brief expansion, the heat was transferred from the bolt head to the bottom, the bolt began to expand and stretch, and the bolt axial force decreased. The second stage lasts about 2 to 3 minutes, and the rapid increases of the axial force in the first stage were caused by the vast amount of heat energy input to the bolt head during the laser treatment. The surface temperature can reach 1000℃ in an instant [7], causing the thermal expansion of the bolt head and washer[10, 11]. This stage occurs within the first 20s. During this stage, all of the bolt axial force increased by about 5%. After a brief expansion, the heat was transferred from the bolt head to the bottom, the bolt began to expand and stretch, and the bolt axial force decreased. The second stage lasts about 2 to 3 minutes, and the reduction of axial force positively correlated with the laser irradiate duration. For specimen S-1, the axial force is reduced by about 5% in maximum, and for S-2 reduced by 15%, such a severe axial force loss is considered unsafe. In the third stage, as the heat energy is transferred from the bolts' head to the bottom and gradually cools down, the temperature in the bottom of the bolt reaches the maximum and the bolt begins to contract so that the bolt axial force is restored. For specimen S-1, the maximum temperature of the bolt increased by 15℃, and for S-2, it increased by about 45℃. The temperature change of the screw part was less than 100℃, so the bolt will not suffer from cracks and brittleness caused by heat[12, 13]. In the last stage, the bolt axial force restore is significantly different due to the different irradiation durations. Form S-1, the axial force was restored by about 2%, and for S-2 was about 10%. The final axial force loss of S-1 and S-2 were 3% and 5%. From the beginning of the laser irradiation to cooling to room temperature, the entire process takes about 30 minutes.

For the single irradiation condition, it can be seen that the F_{min} of specimen S-2 tends to be unsafe, which is lower more than 10% compared with F_0, directly related to the input thermal energy and the thermal expansion of the bolt. Therefore, consider irradiating the bolt head multiple rounds. Fig.2(b) shows that irradiated multiple on the bolt head after the specimen S-1 was sufficiently cooled. The duration of each round irradiation was the same as the first-round irradiation's 20s. After the second round of laser irradiation, cool down in the room environment for 30 minutes and repeat. After repeating three rounds in total, the total laser irradiation duration of S-1 was the 80s, the same as S-2. From Fig.2(b), the highest temperature of each repeat irradiation on S-1 was within the range of 15-20℃. During each round irradiation, the bolt axial force change also shows the similar four stages. F_{max} does not change much after each irradiation, which is about 5% higher than F_0.

Moreover, F_{min} decreased slightly with the increase of irradiations, reaching the minimum of 7% at the fourth irradiation, safer than S-2's 15%. F_s also decreases with the increase of the number of irradiations, but the ratio decreases gradually. The first-round irradiation dropped 2.78%, the second and third rounds only dropped 0.87% and 0.78%, and the last round had almost no change by 0.03%. The total axial force loss after multiple irradiations on S-1 was 4.4%, less than 5% of S-2. Therefore, it can be concluded that multiple irradiations on bolt heads can achieve a higher degree of safety in the corrosion maintenance engineer.

To know the relationship between the bolt's axial force loss ratio F_s/F_0 with the irradiation duration, Fig.3 plotted the fitted $F_s/F_0 - t$ curve. It was found that the axial force loss was in a logarithmic relationship with the accumulated irradiation duration and had good accuracy. The fitting formula can help plan the bolt head maintenance with the CW-laser irradiation.

According to the above test results, the F_{max} of the bolt during laser irradiation was raised about 5% and had no relationship with the irradiation duration. The local expansion and deformation on the bolts[11] and washers only happened in the first 20s and the axial force change did not increase with the irradiation duration up. However, F_{min} and F_s change are directly related to the irradiation duration. The input thermal energy difference leads to a difference in elongation of the bolt. In the process of bolt elongation and contraction, the relaxation and clamping change directly cause the bite between the thread and the nut to form a dislocation, thus causing the loss of axial force. The greater the bolt temperature change, the higher the bolt bite and dislocation, affecting the axial force loss.

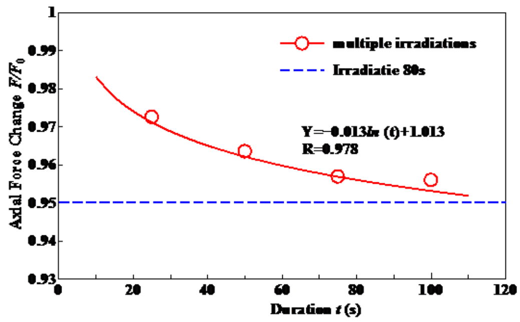

Figure 3. Fitted curve of $F_s/F_0 - t$

Compared with the single long-term laser irradiation, the final axial force loss of the bolts multiple irradiated was significantly reduced. In multiple irradiations, F_{min} is only related to the longest irradiation duration, which was determined by the relationship between the highest temperature and the longest elongation of the bolt. In addition, after the first round of laser irradiation, the bite dislocation of thread and nut has occurred. In the second round of irradiation, the bite dislocation is less affected caused by the first irradiation, so that the axial force loss in the second irradiation is reduced.

IV. CONCLUSIONS

Using a 3kW CW-laser to perform laser surface treatment on the head of F10T M22 high-strength bolts for different periods, the relationship between the change in bolt axial force and the treatment was obtained. The conclusions were as follows:

1. The bolt axial force change was divided into four stages during the laser treatment: 1) the axial force rises to F_{max}, 2) the axial force falls to F_{min}, 3) the axial force recovery, and 4) the axial force stable in F_s;

2. The increase of the bolt axial force during the laser treatment was no more than 5% of the axial force before the treatment, which has no relationship with the laser irradiates duration. The maximum reduction of axial force was only related to the irradiate duration. The longer the irradiation duration, the more significant the axial force reduction.

3. The equation of axial force loss with irradiation time during multiple irradiations on bolt head was fitted, conforms to the logarithmic relationship, and has good accuracy, which can be used as a reference for making maintenance plan.

4. The method of multiple laser irradiation can reduce the maximum axial force reduction and less axial force loss under the same processing period. For severe corrosion conditions of high-strength bolts, it was recommended to use multiple laser irradiation methods for maintenance.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Qidi Wang and Shusen Zhuang: Conceptualization, methodology, formal analysis, investigation, writing and editing. Shigenobu Kainuma: Conceptualization, Resources, supervision, project administration, funding acquisition. Peng Huo: resources, editing, funding acquisition. All authors had approved the final version.

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REFERENCES

[1] L. Lindquist. Corrosion of steel bridge Girder anchor bolts. (2008). Accessed: Oct. 24, 2021. [Online]. Available: http://hdl.handle.net/1853/24649

[2] T. Masayuki, N. Yoshitomo, S. Tetsuhiro, and T. Yoshiaki, "Residual clamping force for corroded tension-control bolts," *Journal of Structural Engineering*, vol. 147, no. 3, p. 04020343, Mar. 2021.

[3] J. H. Ahn, J. M. You, J. Huh, I. T. Kim, and Y. S. Jeong, "Residual clamping force of bolt connections caused by sectional damage of nuts," *Journal of Constructional Steel Research*, vol. 136, pp. 204–214, 2017.

[4] T. Masayuki, S. Tetsuhiro, N. Yoshitomo, A. Yasunori, and Y. Tetsuya, "Dependence of residual axial force on thickness and shape in corroded high-strength bolts," *Journal of Structural Engineering*, vol. 144, no. 7, p. 04018069, Jul. 2018.

[5] I. T. Kim, J. M. Lee, J. Huh, and J. H. Ahn, "Tensile behaviors of friction bolt connection with bolt head corrosion damage: Experimental research B," *Engineering Failure Analysis*, vol. 59, pp. 526–543, 2016.

[6] M. Li, L. Yao, S. Zhang, D. Wang, Z. He, and G. Sun, "Study on bolt head corrosion influence on the clamping force loss of high strength bolt," *Engineering Failure Analysis*, vol. 129, p. 105660, 2021.

[7] S. Zhuang, S. Kainuma, M. Yang, M. Haraguchi, and T. Asano, "Investigation on the peak temperature and surface defects on the carbon steel treated by rotating CW laser," *Optics & Laser Technology*, vol. 135, p. 106727, 2021.

[8] E. G. Hantouche, K. K. Al Khatib, and M. A. Morovat, "Modeling creep of steel under transient temperature conditions of fire," *Fire Safety Journal*, vol. 100, Sep. 2018.

[9] S. A. Moeller, "Relaxation in bolted assemblies," 2016.

[10] M. D'Antimo, M. Latour, G. F. Cavallaro, J. P. Jaspart, S. Ramhormozian, and J. F. Demonceau, "Short- and long- term loss of preloading in slotted bolted connections," *Journal of Constructional Steel Research*, vol. 167, p. 105956, 2020.

[11] M. A. Shaheen, A. S. J. Foster, L. S. Cunningham, and S. Afshan, "Behaviour of stainless and high strength steel bolt assemblies at elevated temperatures — A review," *Fire Safety Journal*, vol. 113, p. 102975, 2020.

[12] Y. Hu, C. B. Yang, L. H. Teh, and Y. B. Yang, "Reduction factors for stainless steel bolts at elevated temperatures," *Journal of Constructional Steel Research*, vol. 148, Sep. 2018.

[13] X. P. Pang et al., "Physical properties of high-strength bolt materials at elevated temperatures," *Results in Physics*, vol. 13, JunE 2019.

Qidi Wang Ph.D. candidate of Kyushu University at the department of Civil Engineering, Japan. His main research areas are steel structure and corrosion engineering.

Shigenobu Kainuma professor at Kyushu University, Department of Civil Engineering. His research fields mainly focus on corrosion and steel structures.

Shusen Zhuang Ph.D. of Kyushu University at the Department of Civil Engineering. He is mainly engaged in the research of structural engineering and laser technique.

Peng Huo engineering of Toyokoh Inc., Japan. He is mainly focusing on laser transmitters development and engineering use.