An Investigation on Axial Force Reductions of High-strength Bolts by Induction Heating for Paint-coating Removal

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Abstract: Removal of anti-corrosion paint is key to the maintenance of aging structures. Previous investigations showed that heating high-strength bolts for coating removal reduces their axial strength. Herein, a series of experiments were conducted to investigate the effect of heating rate on axial force reduction, in search of possible methods to suppress this reduction. The high-strength bolts were heated to 200℃, at different heating rates, and the changes in axial force were estimated, by measuring the strain at the bolt shafts as the temperature increased. The mechanism of the axial force reduction could be explained by the strain behavior at the bolt shafts. The results showed that the shorter the heating time was, the more the axial force was reduced, suggesting that heating bolts over 15-30 seconds suppressed the axial force reduction to 5% of the initially installed axial force of the high-strength bolts.

Keywords: Paint-coating removal; induction heating; bolted joints; axial force

1 Introduction

The maintenance and management of bridge structures are important for their long-term use in sound condition. In the case of steel structures, corrosion is one of the main causes of damage and deterioration. Therefore, several corrosion protection methods have been established and applied to the steel structural members according to the importance of the structure, the expected service life, and the environmental conditions in which the structure is placed [1].

Paint-coating is used as a general corrosion protection method as it balances ease of manufacture, cost, and durability. Many paint-coating systems have been proposed for steel structures in consideration of their environmental corrosion conditions and expected service life [2] [3]. However, deterioration of the paint coating is inevitable over the long-term use of steel structures regardless of the system used. The deteriorated paint coating is renewed at specified intervals to keep the soundness of the coated structures.

When renewing the paint coating, the removal of the existing coating and any rust on the structure significantly influences the performance of the newly applied coating. It has been demonstrated that the sufficient removal of deteriorated paint-coating and rust, and proper preparation of the substrate steel surface affects the durability of the renewed paint [4]. Power tools, blasting, and chemical agents are widely used in the removal of coatings and rust [5]. However, power tools and blasting generate noise and scatter dust in the air, so care is required to control these environmental impacts. Although the use of chemical agents is effective for reducing noise and dust, the amount of waste increases as both the removal agent and the removed paint coating mixed in the agent need to be disposed of. To address these problems, a new paint-coating removal method using a heating device has been developed.

In this method, the paint-coated steel structural members are heated to around 200ºC to soften the paint coating so it can be easily removed with scrapers or other hand tools. Induction heating (IH), which can quickly heat a localized part of the steel material, is used as the heat source for removing the paint-coating from steel structures [6-9]. IH is effective for removing the paint-coating on flat and wide steel members, such as the web plates or deck plates of steel girders. However, it is ineffective in removing coatings from members with complicated geometric shapes, such as connecting parts. This makes coating removal on high-strength bolted joints inefficient when using IH, as the bolts must be heated and the paint-coating removed individually. To facilitate more efficient removal, the authors previously developed an electric heating device capable of heating multiple bolts simultaneously. Although the heating device facilitated the removal of the paint-coating from bolted joints, there was a possibility that heating the bolts excessively would reduce the axial force in the bolts [10]. Possible methods to suppress this loss in bolt axial force and the mechanism for such loss have not been sufficiently elucidated.

This study aims to investigate the bolt axial force reduction mechanism when a bolt is heated for paint-coating removal. A series of heating experiments were conducted on the bolted joint specimens using an IH device. The changes in the axial forces of bolts were examined by measuring the bolt shaft strain before and after heating. Subsequently, a discussion on the reasons for the changes in the axial forces of bolts by heating was conducted based on the results from these measurements. Furthermore, based on the experimental results, suggestions were made for conditions to suppress axial force reduction in the paint-coating removal work.

2 Experiment

2.1 Pre-Heating of High-strength Bolts and Temperature-Correcting Strain Data

In this study, high-strength bolts were heated and the elongations of the bolts were measured by strain gauges attached to the bolt shafts. Previous investigations demonstrated that measured strain values obtained by the gauges included the expansion of the adhesive attaching the gauges to the specimens as temperature changed, and that pre-heating the specimens once after the application of adhesive minimized adhesive creep in subsequent strain measurements. Therefore, the bolts used in this study were pre-heated to compensate for the expansion of the adhesive with temperature affecting the strain measurement. Additionally, the relationship between strain value and temperature was obtained through a pre-heating experiment to examine the measurement accuracy of the real strain on the bolt.

Figure 1 shows the installation of heat-resistant strain gauges (applicable temperature: 350ºC) and thermocouples to the bolt shaft. F10T M22 high-strength bolts were used. Table 1 shows the mechanical properties of the bolt in the mill sheet. The opposite sides of the bolt shaft were machined. Then, two strain gauges and two thermocouples were placed symmetrically at the center of the bolt axis. The reason why the strain gauges were placed symmetrically was to eliminate the influence of bending on the bolt shaft by averaging the strain outputs on both sides of the bolt shaft. The wires were routed through the holes in the bolt head.

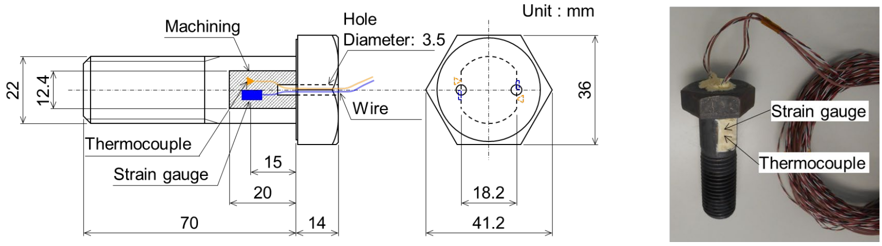


Figure 1

Installing strain gauges and thermocouples to a high-strength bolt

Table 1

Mechanical properties of the F10T M22 high-strength bolt

	Yield stress (N/mm^2)	**Tensile strength (N/mm^2)**	**Elongation (%)**	**Drawing (%)**	**Rockwell hardness HRC**
F10T M22	1033	1087	19	73	33

It has been reported that organic paint-coating materials, such as alkyd resin, deteriorate when heated over 170ºC [11] [12]. Furthermore, a previous study showed that the mechanical properties of high-strength bolts did not deteriorate when heated under 300ºC [13]. From these observations, the heating temperature for removing the paint-coating from high-strength bolts was set at 200ºC [10].

Three high-strength bolts, each attached with two strain gauges, were heated to 200ºC in an electric furnace. The strain was measured as the temperature increased. Figure 2 shows the relationship between the temperature, T, and the measured strain, $\Delta\varepsilon$. Due to the material characteristics of the polyimide resin adhesive used for attaching the strain gauges to the bolts, the measured strain varied with the temperature. The approximation curve of the relationship between the temperature, T, and the measured strain, $\Delta\varepsilon$, was fitted by Eq. (1).

$$\begin{aligned}\Delta\varepsilon = &-6.74 \times 10 + 4.15 \times T - 6.44 \times 10^{-2} \times T^2 \\ &+ 2.43 \times 10^{-4} \times T^3 - 1.34 \times 10^{-7} \times T^4 \qquad (1)\end{aligned}$$

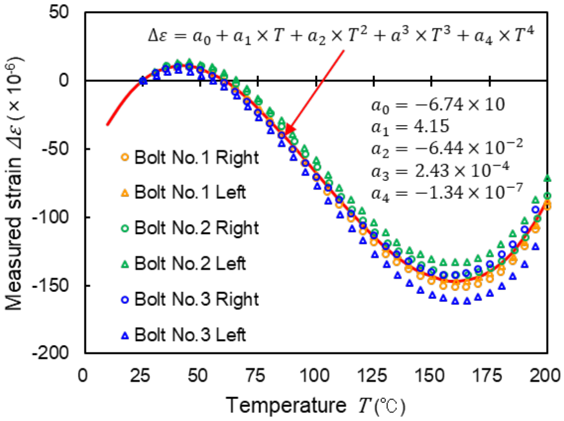


Figure 2

Relationship between the temperature and the measured strain

From the approximation curve, the strain data, ε_1, was corrected using Eq. (2) to obtain the corrected strain value.

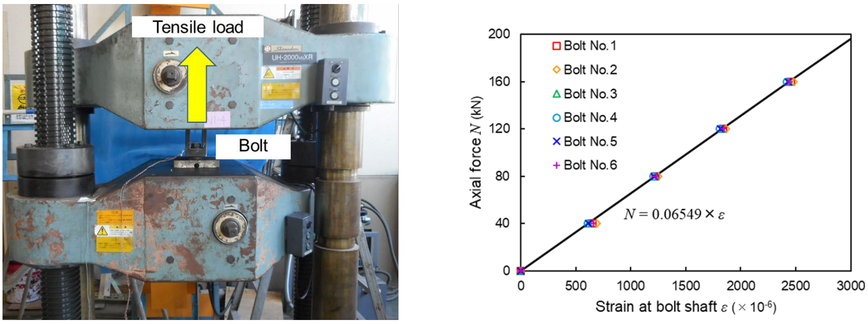
$$\varepsilon = \varepsilon_1 - (\Delta\varepsilon_1 - \Delta\varepsilon_0) \qquad (2)$$

Where ε is the corrected strain data corrected for temperature, ε_1 is the measured strain data at temperature T_1, $\Delta\varepsilon_1$ is the strain value calculated using Eq. (1) with temperature T_1, and $\Delta\varepsilon_0$ is the strain value calculated using Eq. (1) with temperature T_0, where the initial strain data was measured and set as zero.

2.2 Relationship between Bolt Axial Force and Strain

In this study, the bolt axial force was estimated from changes in bolt shaft strain. This estimation required the relationship between the bolt axial force and bolt shaft strain be obtained, and a calibration test was conducted to establish the formula for this estimation. To this end, tensile loads were applied to bolts with strain gauges. The bolts used in this test were pre-heated to 200ºC to eliminate the influence of adhesive expansion. After the temperature of the bolts cooled down to room temperature, the tensile test was conducted.

Figure 3 (a) shows how the calibration test was set up. Six high-strength bolts were used in the calibration test. Tensile loads of 40 kN, 80 kN, 120 kN, and 160 kN were gradually applied to the bolts three times. The magnitudes of the tensile loads were limited in the elastic range. Linear regression was applied to the relationship between the bolt axial force and the strain as shown in Figure 3 (b).



(a) Calibration test setup (b) Relationship between axial force and strain

Figure 3

Calibration test to measure the relationship between bolt axial force and strain

Based on the regression formula shown by Eq. (3), the bolt axial force was estimated using the temperature-corrected strain described in the previous section.

$$N = 0.06549 \times \varepsilon \tag{3}$$

Where, N is the estimated axial force (kN). ε is the strain with the temperature compensation.

2.3 Shape and Dimension of Joint Specimen

Figure 4 shows the specimen, an analogue for a high-strength bolted joint. A base plate was sandwiched by two splice plates. The material of the base plate and the splice plates was SS400. The thickness of the plates was 9 mm. Four high-strength F10T bolts were tightened to join the plates. The material properties and the chemical compositions of steel plates are shown in Table 2.

The purpose of this study is to investigate the influence of heating on the axial forces of high-strength bolts. Therefore, the specimens were not paint-coated and were merely heated under the same conditions as those for paint-coating removal. The surfaces of the plates were cleaned by blasting. The surfaces of the bolts were left covered with mill scale. Three specimens were used.

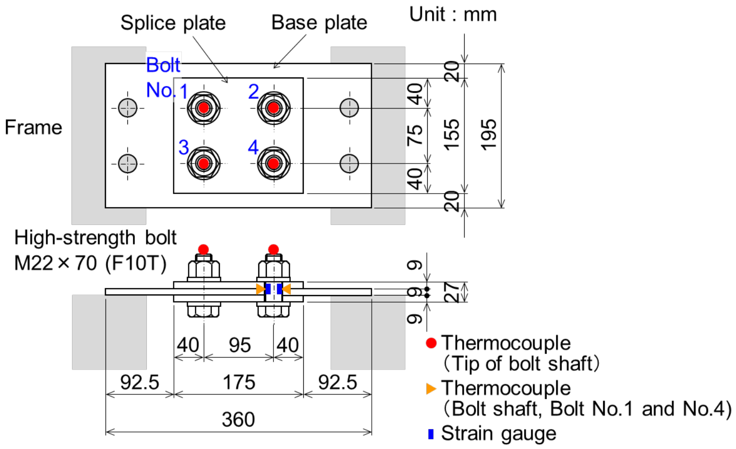


Figure 4
High-strength bolted joint specimen

Table 2
Mechanical properties and chemical composition of steel plate

	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	Chemical compositions (mass %)				
				C	**Si**	**Mn**	**P**	**S**
SS400	334	477	27	0.16	0.14	0.74	0.024	0.006

As shown in Figure 1, strain gauges and thermocouples had been attached to six bolts for the calibration test in the previous section. Two of these bolts were installed on three specimens as bolts No. 1 and No. 4.

For bolts No. 2 and No. 3 in each specimen, strain gauges were attached to the bolt shafts. However, thermocouples were not attached to the bolt shafts due to the limited number of measuring channels of the data logger used in the heating experiment. A thermocouple was attached to the tip of each bolt shaft to measure the temperature from heating.

The high-strength bolts in the specimens were tightened to a specific axial force. The magnitude of the installed axial force was 226 kN, 10% higher than the designed axial force of 205 kN for F10T [14]. The high-strength bolts were manually tightened first, then tightened individually by an electric wrench to 60% of the target axial force. Finally, the bolts were tightened to the target axial force by the electric wrench. After the tightening, relaxation and creep in the bolts reduced the axial forces. Therefore, the heating experiment was conducted over 2 weeks after the tightening. During this tightening process and waiting time, the strain was measured every 10 minutes.

2.4 Heating Experiment

Figure 5 shows how the heating experiment was set up. The IH device used in this study was RPR1032 [15]. The ring-type head of the device was applied to the nut side of the high-strength bolts in the specimens. The temperatures were measured by the thermocouples at the tips of the bolt shafts. The temperature required for paint-coating removal was around 200ºC. Although the target temperature was uniform across all experiments, the heating time was changed. Here, the heating times were parametrically changed while keeping the target temperature of 200ºC constant. The heating times were set to 3, 15, and 30 seconds by arranging the outputs of the IH device. The temperatures and strains of bolts No. 1 and No. 4 were measured at intervals of 0.1 seconds during the heating experiment. To complete the relaxation and creep of the bolts, the specimens were kept for over 2 weeks after the heating experiment.

The changes in the axial forces were evaluated by dividing the reduced axial forces by the initial axial forces (the axial force reduction ratio). Furthermore, the estimated axial forces were confirmed to be around zero when the bolts were completely released from the specimens after the experiment.

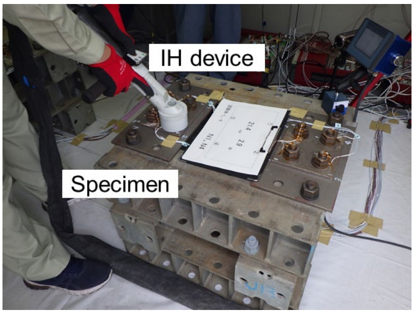


Figure 5

Heating experiment setup

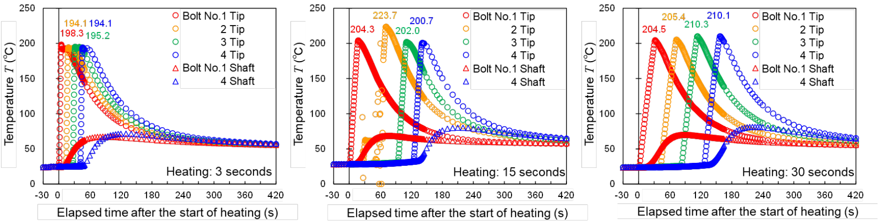
3 Result and Discussion

3.1 Temperature History

Figure 6 shows the temperature histories of the bolts during the heating experiment. The maximum temperatures of the tips of the bolt shafts were observed 1 to 2 seconds after the heating routine was finished. The target temperature of 200ºC was achieved in all tested conditions. The temperatures at the middle of the bolt shafts (bolts No. 1 and No. 4) to which the strain gauges were attached reached maximum temperatures of 70 to 80ºC. The maximum temperatures at the middle of the bolt shafts were observed 40 to 60 seconds after the time when the maximum temperatures at the tips of the bolt shafts were observed.

In specimen No. 2, the temperature of bolt No. 2 changed discontinuously because the IH device was accidentally stopped shortly after the start of heating. The heating routine was briefly restarted, resulting in the maximum temperature at the tip of this bolt shaft being around 20ºC higher than those of other bolts.

It was expected that the temperature of the bolts would cool to room temperature more quickly under faster heating conditions than slower long heating conditions. However, the temperature of the bolts became uniform 300 to 400 seconds, after heating was finished, for all conditions.



(a) Heating time of 3 seconds (b) Heating time of 15 seconds (c) Heating time of 30 seconds

Figure 6

Temperature histories

3.2 Change in Bolt Axial Force

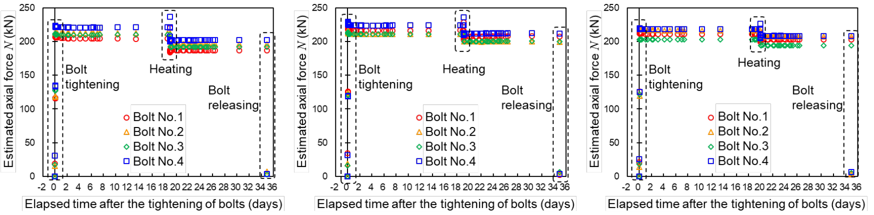
Figure 7 shows the changes in bolt axial forces estimated by the strain measurement. The strain measurement at the bolt shafts was started before the bolts were tightened. Measurement continued during the heating and after releasing the bolts. The bolt axial forces were estimated by Eqs. (1), (2) and (3).

Although the installed axial forces to the bolts by tightening were slightly reduced by creep and relaxation, the axial forces became uniform within approximately 3 days. The axial forces increased temporarily when the bolts were heated. However, the axial forces decreased after the heating. This phenomenon will be discussed later.

The axial forces after the heating were uniform, then the axial forces became almost zero when the bolts were released from the specimens.

In all specimens, the strains at the bolt shafts were measured at intervals of 0.1 seconds in bolts No. 1 and No. 4 during the heating. Figure 8 shows the changes in the axial forces of bolts No. 1 and No. 4 over time, focusing on the period around the heating process. The axial forces increased shortly after the start of heating and decreased when the heating was finished. The axial forces then decreased gradually during the cooling process.

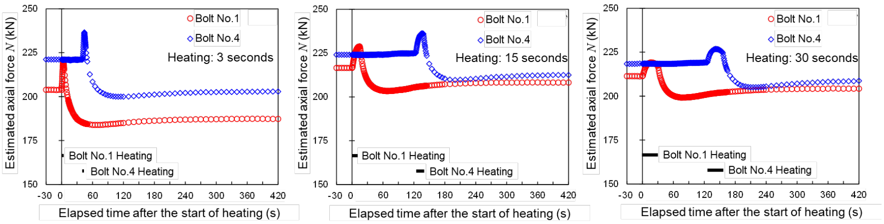
A greater change in the bolt axial forces was observed when the bolts were heated to the target temperature over 3 seconds compared to when the bolts were heated over 30 seconds. An intermediate result between the two was observed when the bolts were heated over 15 seconds. The bolt axial forces increased by 16 kN, 12 kN, and 8 kN for heating times of 3 seconds, 15 seconds, and 30 seconds, respectively. The subsequent decreases in the bolt axial forces during cooling were 36 kN, 25 kN, and 21 kN for heating times of 3 seconds, 15 seconds, and 30 seconds, respectively.



(a) Heating time of 3 seconds (b) Heating time of 15 seconds (c) Heating time of 30 seconds

Figure 7

Change in bolt axial force

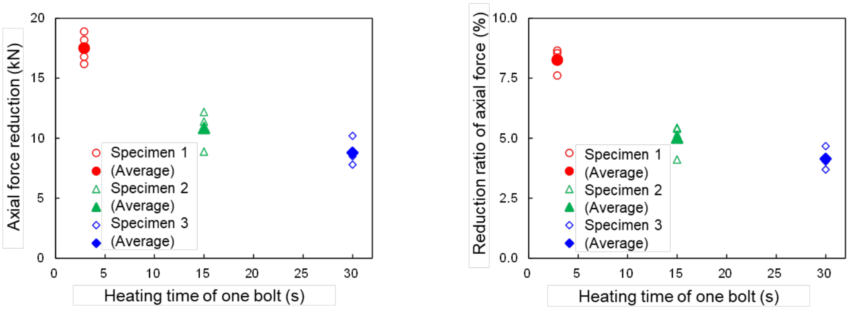


(a) Heating time of 3 seconds (b) Heating time of 15 seconds (c) Heating time of 30 seconds

Figure 8

Change in bolt axial force before and after heating

Figure 9 shows the relationship between the heating time and the reduction of the bolt axial force (also the reduction ratio of the bolt axial force). There is a clear correlation between the reduction of the bolt axial force and the heating time, and for paint-coating removal, high-strength bolts should be heated to the target temperature over a longer period of time to suppress the axial force reduction. Although the experimental conditions in this study were limited, the axial force reduction of high-strength bolts could be kept within 5% of the initial axial force when the heating time was over 15 seconds for a bolt being heated to 200ºC for the purposes of paint-coating removal.



(a) Axial force reduction

(b) Reduction ratio of axial force

Figure 9

Relationship between heating time and axial force reduction

3.3 Mechanism of Change in Bolt Axial Force

Figure 10 shows a potential mechanism explaining the increase and decrease in bolt axial force during the heating and cooling processes.

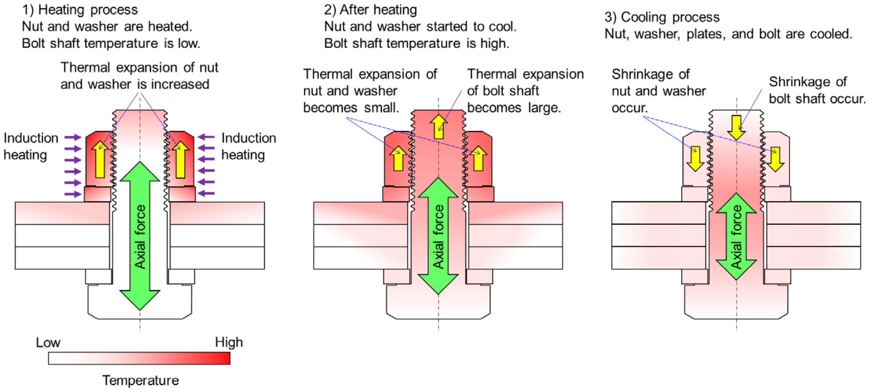


Figure 10

Mechanism of axial force reduction by heating

In this study, the nut side of the joint was heated by the IH device, resulting in a rapid increase in temperature for the nut. The heat had yet to reach the bolt shaft, so the bolt shaft was stretched by the expansion of the nut. We propose this as a possible explanation, as to why the bolt axial force increased during the heating process. After heating, the temperature of the bolt shaft increased gradually via thermal conduction from the nut, while there was no further temperature increase in the nut itself. As shown in Table 3.1 in EN 1993 1-2, the elastic modulus of carbon steel decreases by 10% at 200ºC compared to room temperature [16]. When the temperature of the bolt reached 200ºC, it might be slightly softened due to the temperature rise. A possible explanation as to why the bolt axial force decreased shortly after heating is that there was more expansion in the bolt shaft relative to the expansion of the nut as heat was no longer being applied. In the cooling process, the shrinkage of the nut and the bolt shaft occurred. In the early stage of the cooling, the shrinkage of the nut might be larger than that of the bolt shaft. Due to the difference in shrinkage between them, the bolt axial force slightly increased during the cooling process. However, the axial force might not recover to the initial state after the joint had cooled sufficiently, to the point where there was a negligible temperature difference between the nut and the bolt shaft.

Based on the experimental results, the reduction of the bolt axial force occurred shortly after heating, with maximum reduction of the bolt axial force when the temperature difference between the nut and the bolt shaft are potentially at their greatest.

A quicker heating process increased the temperature difference between these two components, therefore justifying why the axial force reduction was larger when the specimen was heated over 3 seconds compared to the case when the specimen was heated over 30 seconds.

As shown in Table D.1 in EN 1993 1-2, the strength reduction factor for bolts at 200ºC is 0.935 [16] times that at room temperature [16]. The reduction ratio of the bolt axial force obtained in this study was similar to this value for a heating time of 3 seconds as shown in Figure 9 (b). However, the reduction of bolt axial force could be suppressed by prolonging the heating time to 15 seconds or 30 seconds. This is a new finding that can be applied to paint-coating removal processes that use heating in order to preserve the axial force of bolts.

Conclusions

A series of heating experiments were conducted on high-strength bolted joint specimens using an IH device for paint-coating removal. The changes in the axial forces of bolts were examined and the reason for these changes was discussed. The main results obtained are as follows:

(1) An experimental procedure for estimating from the strain at the bolt shaft the bolt axial force as temperature changed was examined. Bolts with strain gauges attached with a resin adhesive were pre-heated to 200ºC to

eliminate the influence of the adhesive expansion on the measurement accuracy. With the influence of adhesive expansion eliminated, the linear relationship between the bolt axial force and the strain value was established by a calibration test.

(2) The nuts of the high-strength bolted joint specimens were heated to 200ºC with varying heating times from 3 seconds to 30 seconds using an IH device for paint-coating removal. It was observed that the longer the heating time was, the larger the reduction of the bolt axial force. The reduction ratio of the bolt axial force was defined as the ratio of the magnitude of the axial force reduction to the initial axial force. The reduction ratios of the axial force were 8.3% when heated over 3 seconds, 5.0% when heated over 15 seconds and 4.1% when heated over 30 seconds.

(3) Based on the experimental results, the mechanism of bolt axial force reduction from heating was estimated. The temperature difference between the nut and the bolt shaft, which was enlarged by the short heating time, might decrease the axial force greatly. As the mechanism of bolt axial force reduction from heating shown in this study was merely an assumption, more investigation will be performed by numerical simulation in future work to prove the validity of this mechanism.

The mechanism of bolt axial force reduction, by heating, as shown, is an assumption based on the experimental results. To prove the validity of this mechanism, more investigations will be performed by numerical simulation in future work.

Acknowledgment

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