

Fatigue Life Improvement by Reducing Welding Residual Stress with Local Heating for Steel Bridge Members

Mikihito HIROHATA^{a,1}, Hiroto NAKATANI^a, Kyong-Ho CHANG^b,
Toshimitsu SUZUKI^c, Hideaki KONISHI^c and Shusuke TOMINAGA^c

^aDepartment of Civil Engineering, Osaka University, Japan

^bDepartment of Civil Environment & Plant Engineering, Chung-Ang University, Korea

^cMM Bridge, Co., Ltd., Japan

ORCID ID: Mikihito HIROHATA <https://orcid.org/0000-0003-4013-7960>

Abstract. This study investigated the possibility of fatigue life improvement by reducing the weld residual stress with local heating for the steel bridge member. A crossing welded part of longitudinal and transverse stiffeners of a steel plate deck was chosen as the target of this study because it is one of the parts prone to fatigue damage in steel bridge structures. To reduce weld residual stresses and improve the fatigue life of this part, the authors applied a local heating method using a high-frequency induction heating (i.e., IH) device. The welded part was heated up to 250 °C for 9 seconds and 550 °C for 30 seconds. This quick and local heating provided the newly generated compressive stress to the welding tensile stress originally existed. Eventually, the tensile residual stress around 200 N/mm² near the weld toe was reduced to less than -30 N/mm². The reduction effect of weld residual stress by local heating on the fatigue life was examined through the experimental approach. The locally heated group had higher durability than that of the non-locally heated group in certain stress ranges.

Keywords. Steel bridge, fatigue, welding, residual stress, local heating

1. Introduction

Fatigue life is one of the most important performances to ensure the long-term durability of steel structures. Generally, fatigue cracks are induced from welds due to stress concentration based on the geometry of the weld and tensile residual stress by welding. To enhance joint performance in the fatigue aspect, several mechanical methods are used to modify the weld joint geometry and reduce stress concentrations [1, 2]. Peening methods are also used to improve the metallurgy of the weld and induce compressive residual stresses around the impact zone [3-5]. Although these methods are effective and widely used to enhance the fatigue performance of welded joints, the machine tool must be mounted to the surface of the welded parts. It might be difficult or impossible to use these mechanical methods for the narrow and complicated structural parts in steel bridges.

To this problem, the authors have proposed a local heating method to improve the weld residual stress state [6-9]. The weld residual stress state is changed by induction

¹ Corresponding Author: Mikihito HIROHATA, E-mail: hirohata@civil.eng.osaka-u.ac.jp

heating (IH) around the welded part locally in this method. IH provides a temperature rise in magnetic materials such as steel due to the electrical resistance to eddy currents generated by induction coils. It is not necessary that the induction coil be attached or brought close to the target position.

This study investigated the applicability of the local heating method to bridge structural members. The improvement effect of the weld residual stress was examined for the connection parts of the longitudinal and transverse stiffeners in steel plate deck structures, which are prone to fatigue damage [10]. Experimental and analytical approaches were conducted on the specimens modeling the welded connection parts of the stiffeners in the steel plate deck. The local heating was applied to reduce weld residual stress. The effect of residual stress reduction was investigated by measuring the stress change. Fatigue experiments were carried out on the groups with and without local heating for comparing their fatigue lives.

2. Experimental specimen

Figure 1 shows the specimen used in this study. The shape and dimension of the specimen assumed the connection part of a longitudinal stiffener and a transverse stiffener in a steel plate deck of a highway bridge. The thicknesses of the longitudinal stiffener and the transverse stiffener were 16 mm and 9 mm respectively. The material of the stiffeners was SM400A, which is a general welded structural steel.

These stiffeners were supported by a thin steel plate of 6 mm thick by tack welding. The longitudinal stiffener was penetrated to the transverse stiffener with a slit of 18 mm wide. These stiffeners were box-welded by gas metal arc welding. The specimen had some holes for fixing a fatigue experimental machine. The number of specimens was 10. The local heating was applied to 5 specimens among them. The other specimens were used as welded for comparison.

3. Local heating condition

3.1. Concept of local heating

Figure 2 shows the concept of the local heating proposed by the authors [8]. At first, the heating is applied to the front of the box welded part. This is named 'heating 1 (H1).' The heated part is expanded during the temperature raising process but the surrounding area with low temperature restrains this expansion. This process generates compressive stress in the heated area. The heated area then shrinks, and this shrinkage is suppressed by the surroundings in the process of lowering the temperature. During this process, tensile stresses are generated in the area subjected to heating. If the magnitude of compressive stress induced in the heating process is larger than that of tensile stress generated in the cooling process, the resultant compressive stress remains. At least, the stress level is intended to be lower than the tensile weld residual stress. The next heating steps are named 'heating 2 (H2) and heating 3 (H3).' The areas sandwiching the box welded parts are heated. Then the tensile stress is produced at the heated part. The equilibrium of forces in the cross-section creates compressive stress in the area apart from the heated area. This is the same procedure to generate weld residual stresses in the weld directional component. By controlling the heating position, compressive stresses

may overlap the inherently existing tensile weld residual stresses at the box welded part. The combination of these heating processes may reduce the original tensile weld residual stress at the box welded part. The effectiveness of this stress reduction concept has been tested in previous studies through experimental and analytical approaches [8, 9].

The heat source of the local heating was an induction heating (IH) device shown in Figure 2. The coil size was 110 mm x 40 mm.

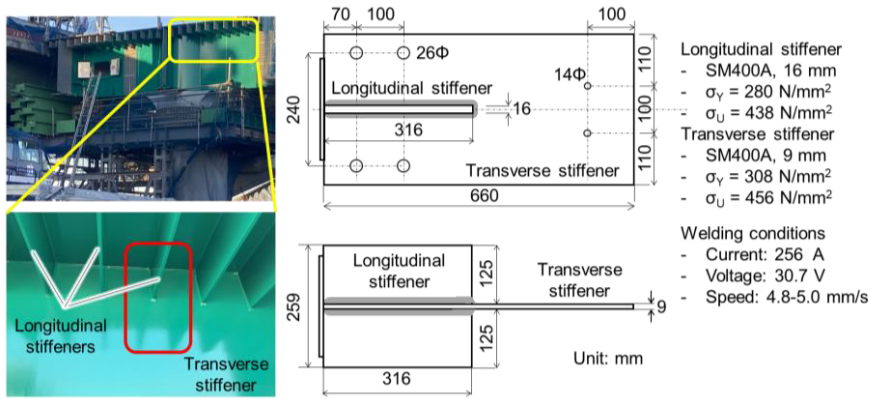


Figure 1. Experimental specimen.

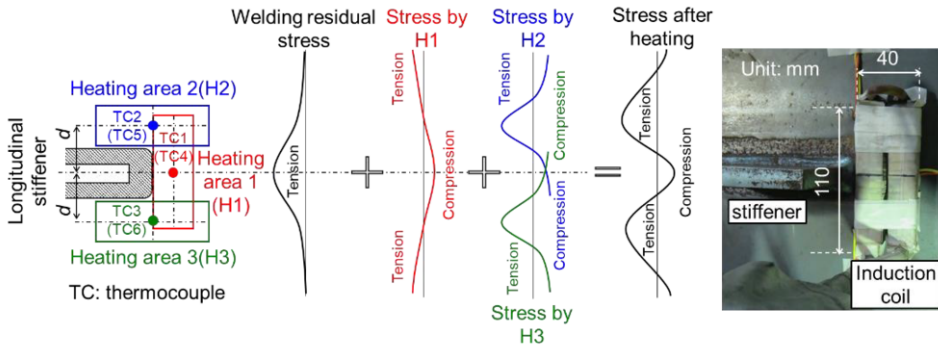


Figure 2. Concept of local heating for stress reduction.

3.2. Identification of local heating condition by numerical simulation

To identify the local heating condition by which the weld residual stresses can be reduced effectively, a series of numerical simulations were conducted [11]. Figure 3 shows the numerical simulation model. The software used for the simulation was Abaqus. The model was composed of solid elements with 8 nodes. A thermal elastic-plastic analysis was conducted by considering the material properties shown in Figure 4. The heat transfer from the outer surface to the air was considered. The rigid body displacement was fixed.

Firstly, the weld residual stress was reproduced. The straight weld line was considered by the uniform heat energy with the welding condition. The heat was applied

at one time along the weld line. The box welded part was considered by the moving heat source based on the welding condition. Eq. (1) provides the heat energy.

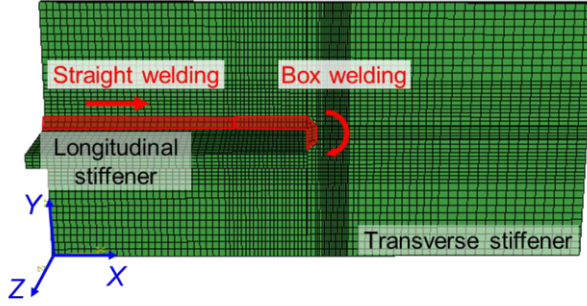


Figure 3. FE simulation model.

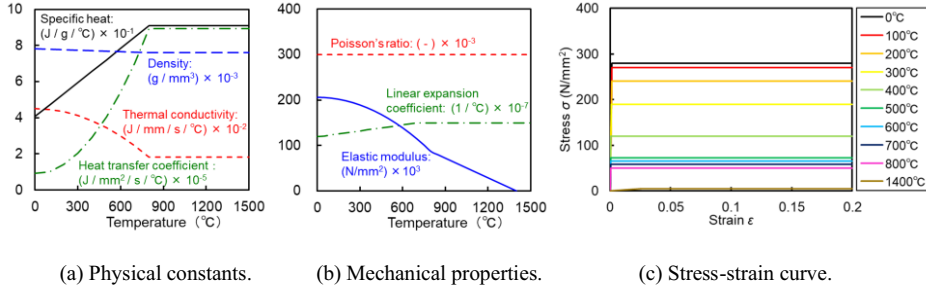


Figure 4. Temperature-dependent material properties.

$$Q = \eta EI / v \quad (1)$$

where, Q is the heat energy (J/mm). E , I , and v are the welding voltage (V), current (A), and speed (mm/s), respectively. η is the thermal efficiency. It is from 0.6 to 0.85 in the general gas metal arc welding. The value of the thermal efficiency was decided by several times of trial analyses for simulating the temperature history during the welding. Figure 5 shows the temperature change in the welding process. The analytical temperature data showed an acceptable similarity to the experimental results. The simulated weld residual stress is shown with the stress reduced by the local heating later.

As described above, the stress reduction mechanism of H1 is different from those of H2 and H3. Therefore, the heating conditions of H1 were examined first. After that, the heating conditions of H2 and H3 were examined. The position of H1 was at the front of the box welded part as shown in Figure 2. Even though the compressive stress occurs in the heating process, the stress after heating will return to the tension side largely if the temperature of H1 is too high. Therefore, the heat energy of H1 should be as low as possible. Numerical simulations of H1 were conducted with varied target temperatures of H1 from 150 °C to 550 °C in 100 °C increments. The heating time was 35 seconds based on the actual results of the device's capacity. The heat flux was given to the area of H1 by monitoring the temperature of the midpoint. The value of the heat flux was adjusted to reach the target value of the monitored temperature.

Figure 6 shows the stress distributions after the welding and the cases with the varied H1 heating. In all cases, the stress was reduced from the welded situation. The stress

reduction of 150 °C heating was smaller than the heating cases of 250 °C, 350 °C, and 450 °C. The stress distributions at the heated and non-heated surfaces were almost the same. In the case of 550 °C heating, the reduced stress in the heating process was largely returned to the tension side in the cooling process. As a result, the stress reduction effect was smaller than the cases of 250 °C, 350 °C, and 450 °C. From the viewpoints of the energy saving and the stress reduction effect, the heating temperature of H1 was decided as 250 °C.

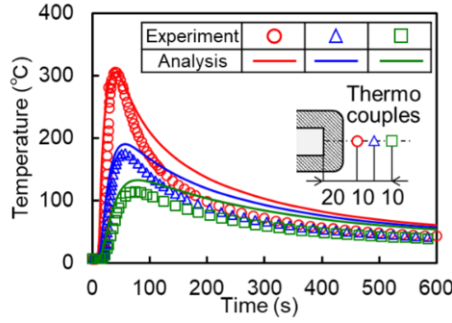


Figure 5. Welding temperature history.

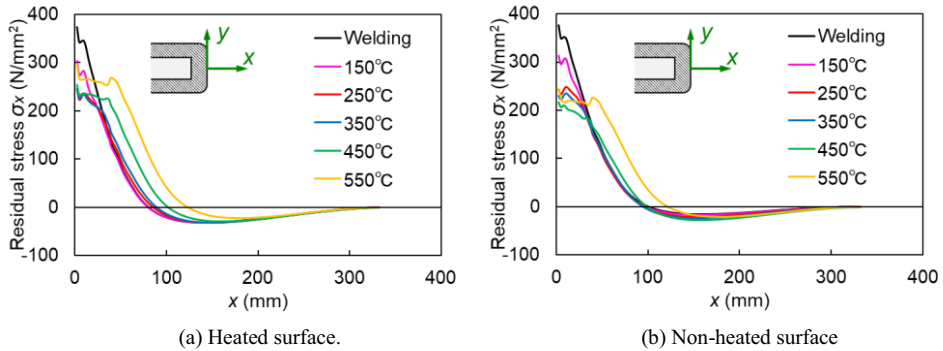


Figure 6. Analysis results of residual stresses.

Continuously, the heating temperature and position of H2 and H3 were examined. In the cases of H2 and H3, the maximum compressive stress generated by H2 and H3 should be adjusted to the target position. Therefore, the heat energy was provided to the simple steel plate model assuming the transverse stiffener only as shown in Figure 7. The target temperature was varied from 250 °C to 550 °C in 100 °C increments as well as the simulation of H1. Numerical simulations were conducted to examine the maximum compressive stress and the position of the heating center at which the compressive stress was maximum.

Table 1 shows the values of compressive stress and the distance from the heating center, d in each heating case. The compressive stress increased with heating temperature, and the distance, d at which large compressive stresses occurred also increased. The maximum compressive stresses of the 450 °C and the 550 °C cases were almost the same. The distances, d of the 450 °C heating case and the 550 °C heating case were 35 mm and 45 mm, respectively. The distance from the heating center should be longer than 40 mm due to the size limitation of the coil width (40 mm) and the thickness of the longitudinal stiffener (16 mm). Therefore, each heating temperature was decided as 550 °C. The position of the heating center was 45 mm away from the midpoint of the box welded part.

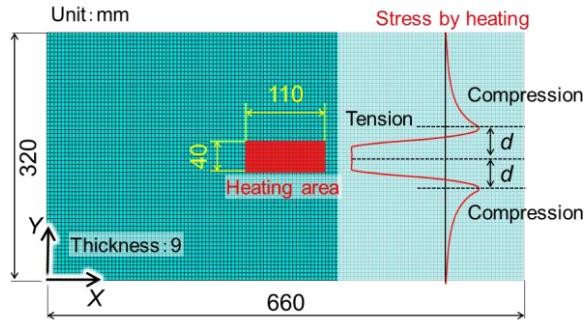


Figure 7. Simple steel plate model.

Table 1. Relationship between heating temperature and magnitude of stress in longitudinal direction.

Heating temperature °C	Distance from the heating center, d mm	Stress in longitudinal direction		Average
		Heated surface	Non-heated surface N/mm ²	
250	20	—33.0	—7.8	—20.4
350	25	—115.2	—93.7	—104.5
450	35	—140.0	—139.9	—140.0
550	45	—133.6	—140.7	—137.2

4. Experimental procedure

4.1. Local heating

The heating conditions for the specimen in this study were decided by the numerical simulation approach. H1 was the front of the box welded part. The distance of 45 mm was fixed from the center of the longitudinal stiffener to the centers of H2 and H3. Only one side of the transverse stiffener was heated because the heating on one side increased the temperature on the opposite side. The thermocouples attached to the center of each heating area monitored the temperature in the heating processes. TC1, TC2, and TC3 were attached to each heating center, respectively. TC4, TC5, and TC6 were attached to the non-heated surface of the transverse stiffener. The positions of TC4, TC5, and TC6 corresponded to the backside of TC1, TC2, and TC3, respectively. The target temperatures were 250 °C for H1 and 550 °C for H2 and H3.

4.2. Stress measurement

An X-ray diffraction method (XRD, μ -360Xs by Pulstec industrial Co., Ltd.) was adopted for measuring the stresses after welding and after local heating, respectively. The longitudinal stress component affecting the fatigue crack in this specimen was measured.

4.3. Bending fatigue experiment

Figure 8 shows the experimental setup of the bending cyclic loading. The specimen was fixed to the steel frame. An eccentric motor was set at the free edge of the specimen. A cyclic bending deformation was applied to the specimen by rotating the motor.

The strain gauges were attached in front of the box weld toe with a distance of 5 mm. The stress range was calculated by multiplying the elastic modulus by the strain range. When a fatigue crack is initiated around the welded part, the crack interrupts the load transfer. Therefore, the strain amplitude becomes smaller. This strain drop phenomenon is used for evaluating the fatigue crack initiation [7-9]. This study noted the loading cycles when the reduction ratio of the strain amplitude reached 5% from the initial value. That loading cycle number was evaluated as the fatigue life.

After confirming the strain drop of 5% from the initial value, applying the cyclic deformation was stopped. Then, the existence of the fatigue crack was examined by magnetic particle flaw detection. When the strain did not decrease and the loading cycle exceeded 3 million, the cyclic loading was finished as run-out.

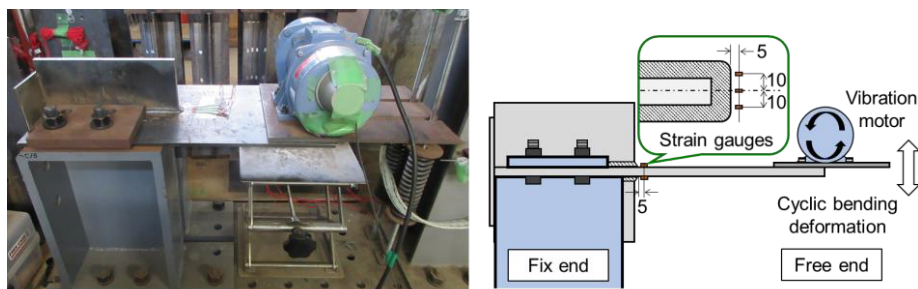


Figure 8. Setup for bending fatigue experiment.

5. Results and discussion

5.1. Temperature history

Figure 9(a) shows the temperature history during the local heating experiment. The temperatures of TC1 and TC4 reached 250 °C by 9 seconds. The temperatures of TC2 and TC5 reached 550 °C by 30 seconds. The temperatures of TC3 and TC6 reached 550 °C by 30 seconds. The results indicated that the target temperatures of H1, H2, and H3 were accurately controlled. Furthermore, the temperatures at the non-heated surface were almost the same as those at the heated surface.

5.2. Change in residual stress

Figure 9(b) shows the residual stress distributions before and after the local heating. The average and the standard deviation of measured values are shown in the figure. The tensile weld residual stresses around the weld toe were decreased on both heated and non-heated surfaces by applying the local heating. The tensile weld residual stress of around 200 N/mm² was reduced to around -30 N/mm² near the weld toe. The results showed the considerable stress reduction effect by the local heating.

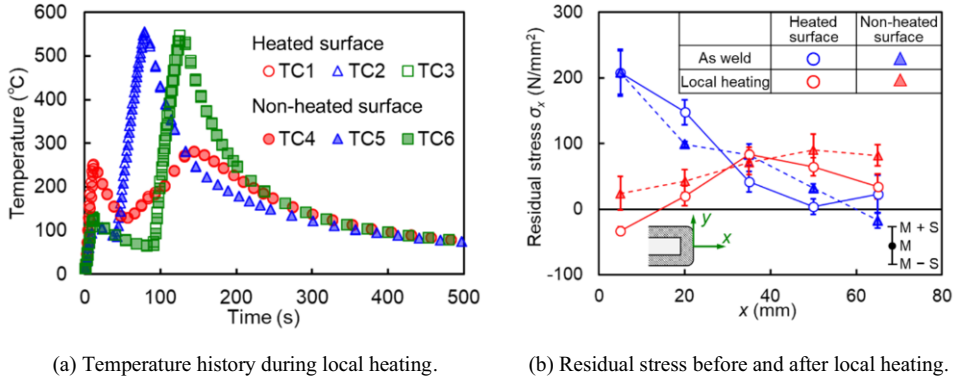


Figure 9. Results of local heating experiment.

5.3. Fatigue durability

Figure 10(a) shows an example of the change in the monitored strain range. The strain range decreased by the cyclic loading. When the ratio of the strain range dropped by 5 % of the initial strain range, the specimen reached the fatigue life. By continuing the cyclic loading, the fatigue crack along the weld toe was observed.

Figure 10(b) shows the results of the bending fatigue experiment. When the stress range was under 140 N/mm², two as-weld specimens had the fatigue life around 500 thousand cycles although the other two as-welded specimens did not show fatigue cracks after 3 million cycles. The fatigue life of one heated specimen was around 1.5 million cycles. The other three heated specimens exhibited fatigue lives in excess of 3 million cycles. The effect of local heating on fatigue life improvement was confirmed, although not as clear.

When the stress range was over 140 N/mm², no clear effect of the local heating on fatigue life was observed. Weld residual stresses in as-welded specimens may be reduced by plastic deformation due to cyclic loading in the high stress range [12]. The stress states of as-weld specimens and locally heated specimens might become similar under cyclic loads. Because the residual stresses were reduced in both the as-weld and the locally heated specimens, the difference in their fatigue life was not observed.

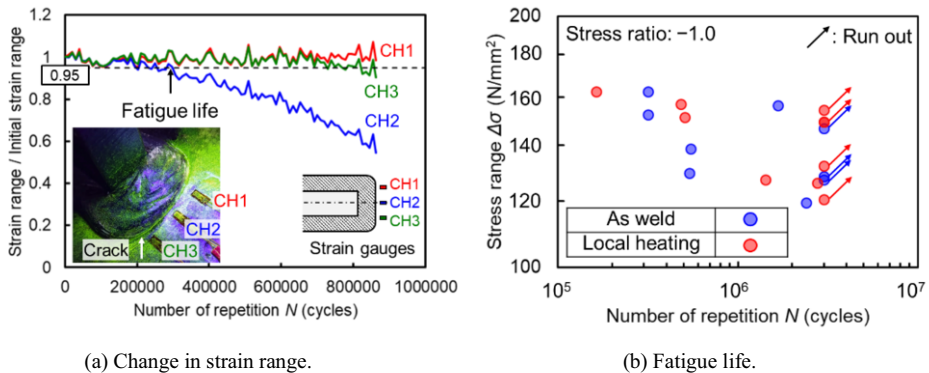


Figure 10. Results of bending fatigue experiment.

6. Conclusions

This study investigated the effect of local heating to improve fatigue durability by reducing the weld residual stress. Experimental and analytical approaches were carried out on the specimens modeling the stiffener connection part of the plate deck in the steel bridge structure. The main results are summarized as follows.

- (1) The local heating experiment was performed on the specimens. A combination of 250°C and 550°C heating steps with an IH device reduced the tensile residual stress around the weld toe. The magnitude of tensile stress was reduced from 200 N/mm² to -30 N/mm² on both heated and non-heated surfaces.
- (2) The fatigue experiment was conducted on the as-weld and the locally heated specimens. If the stress range near the weld toe was 140 N/mm² or less, the fatigue life improvement effect of local heating was confirmed.
- (3) The weld residual stress of the as-welded specimen was reduced by plastic deformation due to cyclic loading. Therefore, the stress states of as-weld and locally heated groups may be similar under cyclic loads. As a result, no enhancement in fatigue durability by local heating was observed under the stress range exceeded 140 N/mm².

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 19KK0366. The local heating experiment was supported by JEMIX Co. Ltd.

References

- [1] L. Huo, D. Wang, Y. Zhang: Investigation of the fatigue behavior of the welded joints treated by TIG dressing and ultrasonic peening under variable-amplitude load, *International Journal of Fatigue*, **27** (2005), 95-101.
- [2] Y. H. Zhang, S. J. Maddox: Fatigue life prediction for toe ground welded joints, *International Journal of Fatigue*, **31** (2009), 1124-1136.
- [3] M. Tai, C. Miki: Fatigue strength improvement by hammer peening treatment—verification from plastic deformation, residual stress, and fatigue crack propagation rate, *Welding in the World*, **58** (2014), 307-318.
- [4] S. Tekeli: Enhancement of fatigue strength of SAE 9245 steel by shot peening, *Materials Letters*, **57** (2002), 604-608.
- [5] G. B. Marquis, Z. Barsoum: A guideline for fatigue strength improvement of high strength steel welded structures using high frequency mechanical impact, *Procedia Engineering*, **66** (2013), 98-107.
- [6] M. P. Aung, M. Nakamura, M. Hirohata: Characteristics of residual stresses generated by induction heating on steel plates, *Metals*, **8** (2018), 25.
- [7] M. P. Aung, H. Katsuda, M. Hirohata: Fatigue-performance improvement of patch-plate welding via PWHT with induction heating, *Journal of Constructional Steel Research*, **160** (2019), 280-288.
- [8] M. Hirohata, M. P. Aung, K. Ani: Residual stress reduction of fillet box welded joints by local heating using induction heating device, *Journal of JSCE*, **8** (2020), 194-206.
- [9] M. Hirohata, K. Ani, T. Suzuki, H. Konishi: Influence of residual stress reduction by local heating on fatigue resistance of fillet box welded joints, *Journal of JSCE, Ser. A1 (Structural Engineering & Earthquake Engineering (SE/EE))*, **77** (2021), 475-488 (in Japanese).
- [10] J. W. Fisher, S. Roy: Fatigue of steel bridge infrastructure, *Structure and Infrastructure Engineering*, **7** (2011), 457-475.
- [11] H. Nakatani, M. Hirohata, K.-H. Chang, S. Tominaga, H. Konishi, T. Suzuki: Analytical study on local heating conditions for reducing residual stress of welded stiffeners in steel plate deck, *Annual Meeting of JSCE*, 2022 Sept 13-15; Hiroshima, Japan, I-381 (in Japanese).
- [12] C.-H. Lee, K.-H. Chang, V. N. V. Do: Finite element modeling of residual stress relaxation in steel butt welds under cyclic loading, *Engineering Structures*, **103** (2015), 63-71.