Welding Process and Consumables Aimed at Improving Fatigue Strength of Joints

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The fatigue of steel structures, an important problem, is mainly attributable to stress concentration and tensile residual stress at their weld toes. In order to improve the fatigue resistance of welds, welding consumables, called low-temperature transformation (LTT) consumables, have been developed and their effectiveness demonstrated. Conventional LTT consumables, however, contain large amounts of Ni, posing problems of high cost, poor mechanical properties and low cracking resistance, which has hindered their widespread use. With this in mind, a study was conducted to replace Ni with Mn, which confirmed that Mn can more effectively improve fatigue resistance than Ni. Two newly developed consumables, "TRUSTARC™ MX-4AD" and "TRUSTARC™ LB-3AD", exploit Mn to improve the crack resistance and reduce cost. When used for additional beads, these welding consumables were confirmed to improve the fatigue resistance as well as or better than other methods such as grinding treatment, a standard method for increasing fatigue strength, or peening treatment, which is becoming widespread.

Introduction

Lately, many steel bridges, such as those on the Tokyo Metropolitan Expressway, are suffering from fatigue cracks due to aging, posing a serious problem. A weld is a portion that can deteriorate structural fatigue resistance due to the stress concentration at the weld toes as well as residual stress. Thus, the technology for improving the fatigue resistance of welds is being looked to with great expectation.

The current techniques for improving the fatigue resistance of welds include grind finishing the shapes of the weld toes to relax stress concentration and peening the welds to introduce compressive residual stress.1) These methods, however, are causing a huge burden due to their low work efficiency and the special apparatuses required.

As a technique for improving fatigue resistance by means of welding consumables, a method has been developed which involves special welding consumables, called low transformation temperature (hereinafter "LTT") welding consumables.2)-4) The LTT welding consumables developed so far, however, are significantly inferior to general welding consumables in terms of consumable cost, mechanical performance and resistance against cracking (delayed cracking and hot cracking), and have not been fully implemented yet.

In order to solve these problems and to develop LTT welding consumables that can effectively improve fatigue resistance, Kobe Steel proposed new composition systems that are different from the ones for the conventional LTT welding consumables. On the basis of newly gained knowledge, the company has started manufacturing two products, the TRUSTARC™ note) MX-4AD (hereinafter "MX-4AD"), a flux-cored wire (FCW) for fillet welding that is widely used in the bridge industry, and the TRUSTARC LB-3AD (hereinafter "LB-3AD"), a shielded metal arc-welding rod superior in all-position welding. This paper introduces these products.

1. Mechanism of improving fatigue resistance by using LTT welding consumables

The technology of LTT welding consumables exploits the phase-transformation expansion of weld beads during the cooling process in relaxing the tensile residual stress caused by welding. As shown in **Fig. 1**, a conventional welding consumable undergoes phase transformation at a temperature of 700℃ or higher, and the thermal contraction of the weld bead after the transformation is restrained by the base material, inevitably causing tensile residual stress. An LTT welding consumable, in contrast, has a transformation-start temperature of 500℃ or lower, allowing the transformation expansion of the weld bead to continue at temperatures closer

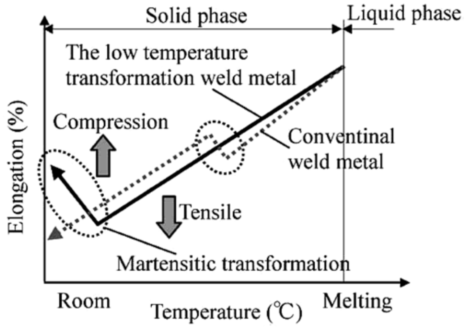

Fig. 1 Mechanism of introducing compressive residual stress around weld bead by low-temperature transformation

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note) TRUSTARC (TRUSTARC™) is a trademark of Kobe Steel.

to the ambient temperature, which enables weak tensile/compressive residual stress to remain after the welding. Many studies have been conducted on the transformation-start temperatures (hereinafter "Ms points") of iron and steel, which, for example, are expressed by Equation (1):[5]

$$\text{Transformation-start temperature (℃)} = 529 - 382\times(\%C) - 31\times(\%Mn) - 18\times(\%Ni) - 9\times(\%Mo) - 5\times(\%V) - 33\times(\%C)\times(\%Cr) \quad\cdots\cdots\cdots\cdots (1)$$

This equation indicates that the transformation-start temperature can effectively be lowered by the addition of elements such as C, Mn, Ni and Cr. Each LTT welding consumable developed so far contains approximately 10% of Ni as the main alloying element, which lowers the transformation-start temperature to 200℃ or below.[6] However, although Ni is effective in lowering the transformation-start temperature, the element deteriorates the resistance against hot cracking, excessively raises the strength of weld beads and increases the cost of welding consumables. This has been hindering the more widespread use of LTT welding consumables. Now, Kobe Steel has developed LTT welding consumables while actively exploiting Mn, which substitutes for Ni and is just as effective in the lowering transformation-start temperature.

2. Additional-welding process

Regardless of its composition system, an LTT welding consumable has the feature of producing a weld bead with high strength and low toughness. This feature contributes to the improvement of the fatigue characteristics of joints; however, it may cause the brittle fracture of welds and deteriorate the resistance against delayed cracking. The drawbacks, therefore, cannot be resolved by simply replacing conventional welding consumables with LTT welding consumables. Hence, the practical use of an LTT welding consumable requires development that takes into account the method of its application.

According to the specifications for highway bridges, the weld toes of fillet joints, including cruciform joints and gusset-plate joints, are easily subject to stress concentration and particularly tend to become the origins of fracture.[7] The application of LTT welding consumables to such parts can be effective in improving the fatigue characteristics. As shown in **Fig. 2** (a), however, when a horizontal plate is abutted against a vertical plate (rib) and the intersection is welded with partial joint penetration to form main beads, by fillet welding, for example, a significant stress concentration occurs at the roots as well as at the toes. As a result, applying an LTT welding consumable to a main bead may lead to cracking at the root, increasing the risk of the structure collapsing in a brittle manner (Fig. 2 (b).) In an attempt to resolve these problems, main beads were formed by a conventional welding consumable for 490 MPa class steel to create a sound weld joint, and an LTT welding consumable was overlaid onto the weld toes of the main beads to relax the tensile residual stress there. This method, so called additional welding, is depicted in Fig. 2 (c) and **Fig. 3**.

Additional welding is also expected to relax the macroscopic stress concentration, thanks to the increased throat depth and leg length of the weld.

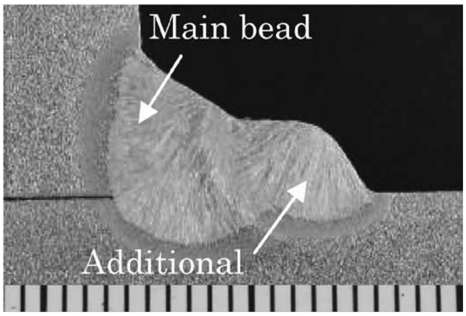


Fig. 3 Cross-sectional shape of additional weld

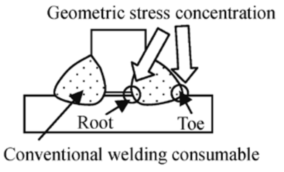
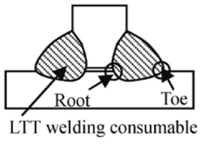
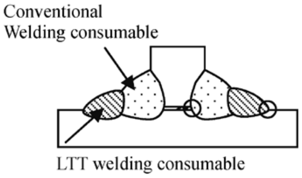
		(a) Conventional welding joint	(b) Welding joint using LTT welding consumables as main bead	(c) Welding joint using LTT welding consumables as additional bead
				
Root	Crack resistance and Toughness	Good	Poor	Good
Toe	Residual stress	Tensile	Compression	Compression
	Fatigue strength	Low	Improve	Improve

Fig. 2 Fillet welding process to balance ①fatigue strength with ② crack resistance and toughness

3. Study on improving fatigue resistance by addition of Mn to welding consumables

3.1 Composition of welding consumables tested

Table 1 lists the flux-cored wires used for the test. The main beads were formed by the FAMILIARC TM note) MX-200 (hereinafter "MX-200"), a product of Kobe Steel, and comparisons were made with reference to it. This welding consumable is the most widely used of the consumables used for the fillet welding of 490 MPa class steels. In order to verify the improvement effect of Mn and Ni on fatigue resistance, tests were conducted on trial FCWs (B - E) that are based on MX-200 and contain various amounts of Mn and Ni.

These test materials were subjected to Formaster testing to measure their transformation temperatures, which confirmed that both Mn and Ni have the effect of lowering the transformation temperature, as known previously. **Fig. 4** compares consumables containing 5% of Mn and Ni respectively. This figure indicates that, compared with Ni, the addition of Mn results in a greater expansion of the deposited metal at the ambient temperature. Thus, a positive addition of Mn is expected to cause compressive residual stress and to improve the fatigue resistance.

Table 1 Mn and Ni content (%) in all-deposited metal and Ms point

Wire	Mn	Ni	Ms point (℃)	Purpose
MX-200	1.7	0	670	Base
FCW B	2.1	3.1	490	Increasing Ni from MX-200
FCW C	2.0	5.2	390	Increasing Ni from MX-200 and FCW B
FCW D	3.6	0	490	Increasing Mn from MX-200
FCW E	5.5	0	310	Increasing Mn from MX-200 and FCW D

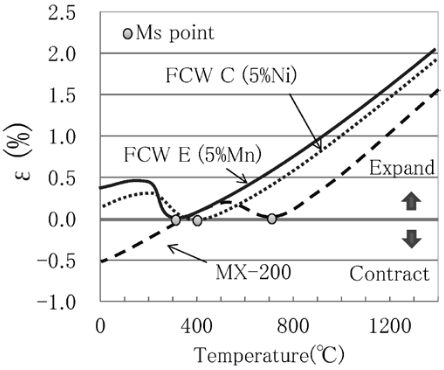


Fig. 4 Relationship between temperature and expansion of conventional welding consumable, FCW C and FCW E

3.2 Methods of residual stress measurement and fatigue test

Base plates of SM490YA (thickness, 12 mm) were joined by double-sided fillet welding to prepare joints as shown in **Fig. 5**. Each joint was subjected to the measurement of residual stress at its weld toe and to a three-point bending fatigue test. It should be noted that, as shown in **Table 2**, all the test joints employed MX-200 to their main beads, while adopting MX-200, FCW B, FCW C, FCW D and FCW E, respectively on their additional welds. The welding conditions were as follows: welding current, 280 A; welding speed, 450 mm/min; and shielding gas, 100% CO_2.

Each test joint, as prepared, was subjected to X-ray residual stress measurement to determine its surface residual stress at its weld toe. This measurement was conducted at the center in the direction of the weld line. The measuring point was 0.5 mm from the weld toe (**Fig. 6**.)

The specimens for the fatigue test were prepared as shown in **Fig. 7**, and a three-point bending fatigue test was conducted with a stress ratio of 0.1. The nominal stress was calculated in accordance with Equation (2):

$$\text{Nominal stress } \sigma \text{ (MPa)} = 3\,PL / 2\,wb^2 \quad \cdots\cdots\cdots \ (2)$$

P : test load (N), L : support span (mm),
w : plate width (mm), b : plate thickness (mm)

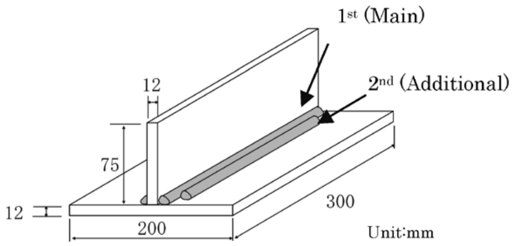


Fig. 5 Test joint and its dimensions

Table 2 Combination of welding wires

Main (1st)	Additional (2nd)
MX-200	MX-200
	FCW B
	FCW C
	FCW D
	FCW E

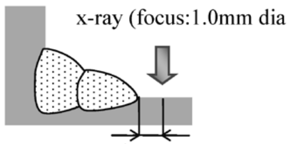


Fig. 6 Schematic of residual-stress measuring point

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note) FAMILIARC (FAMILIARC™) is a trademark of Kobe Steel.

3.3 Effect of Mn addition on relaxation of tensile residual stress and improvement of fatigue resistance

Fig. 8 shows the results of the residual stress measurements at the weld toe of the T-shaped fillet joints. For each 2% increase in the amount of Ni added in the all-deposited metal, the compressive residual stress at the weld toe increases by 20 MPa. In contrast, for each 2% increase in the amount of Mn added, the stress increases by approximately 50 MPa, indicating that this element makes a greater contribution than Ni to the provision of compressive residual stress.

Moreover, the fatigue resistance of joints improves with the addition of Mn and/or Ni, as shown in **Fig. 9**. For convenience, a regression analysis was performed on the 10^5 cycle strength, which yielded Equation (3). This equation implies that, compared with Ni, Mn has approximately twice the effect on the improvement of fatigue resistance.

$$10^5 \text{ cycle strength (MPa)} = 390 + 32 \times (\%\text{Mn}) + 18 \times (\%\text{Ni}) \quad \cdots\cdots (3)$$

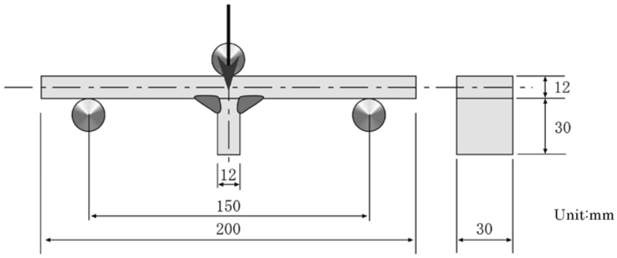


Fig. 7 Schematic of specimen for bending fatigue test

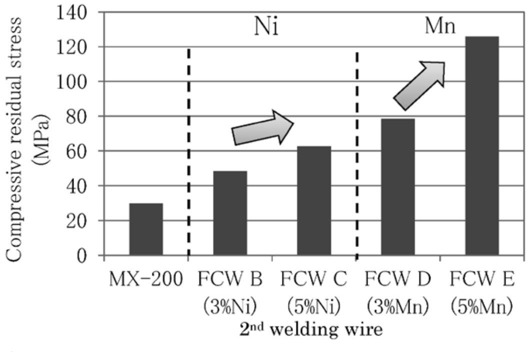
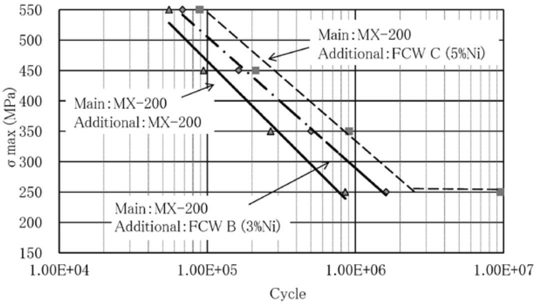
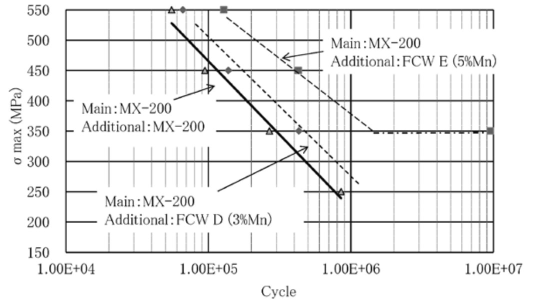


Fig. 8 Effect of Ni and Mn content on residual stress on surface of base metal nearby weld toe



(a) Effect of Ni



(b) Effect of Mn

Fig. 9 Improvement of bending fatigue strength by increased addition of Ni and Mn

(Mn: 1.7 − 5.5 wt%, Ni: 0 − 5 wt%, N = 5 , R = 0.99, R2 = 0.98, Standard error = 6.7)

4. Welding consumables, MX-4AD and LB-3AD, for improving fatigue resistance

4.1 Performance of MX-4AD and LB-3AD

When putting an LTT welding consumable into practice, a necessary and sufficient degree of toughness (47 J at 0℃) must be secured with favorable hot cracking resistance under practical conditions. The welding consumables developed this time, MX-4AD and LB-3AD, contain adjusted amounts of Mn and Ni and are designed to satisfy these requirements (**Table 3**.)

In general, the FCWs of carbon steel systems contain slag sources (oxides), which tend to be left in weld beads as inclusions, making the weld beads low in toughness. Against this backdrop and taking into account the balance between toughness and fatigue strength, the MX-4AD has a Mn content

Table 3 Chemical compositions, Ms points, and mechanical properties of all-deposited metals and results of hot crack test* for developed welding consumables

	Chemical compositions (wt%)						Ms point	YS	TS	El.	absorbed energy	Result of
	C	Si	Mn	Ni	Cr	O	(℃)	(MPa)	(MPa)	(%)	at 0℃ (J)	hot crack test*
MX-4AD	0.029	0.38	4.3	-	-	0.069	472	727	820	23	53	No crack
LB-3AD	0.034	0.41	3.3	3.3	-	0.019	408	895	973	20	72	No crack

*According to JIS Z 3155 FISCO test
※MX-4AD: Welding current 280A-Welding speed 300 and 600 mm/min
LB-3AD : Welding current 140A-Welding speed 150 and 300 mm/min

of approximately 4% in deposited metal. Low-hydrogen covered arc-electrodes, on the other hand, result in low oxygen and less inclusion, thanks to the strong deoxidant contained in the applied flux, which results in weld beads with higher toughness than that obtained by FCW. This, as a result, raises the upper limit for the additive amount of Mn + Ni. In the case of LB-3AD, sufficient toughness and favorable hot-cracking resistance have been secured even with its composition of 3% Mn - 3% Ni in the deposited metal. It should be noted that the hot cracking resistance was evaluated in accordance with JIS Z 3155, based on the restrained weld cracking test with C-type jig (FISCO cracking test). The existence/non-existence of cracks was evaluated at constant regions excluding starts and craters.

As shown in **Fig.10**, the transformation-start temperatures (Ms points) are significantly lower for the MX-4AD and LB-3AD than for the MX-200, a welding consumable of 490 MPa class. In particular, the LB-3AD, containing larger amounts of alloying elements, exhibits a greater transformation expansion at the ambient temperature and is expected to improve fatigue resistance significantly.

4.2 Effect of MX-4AD and LB-3AD on improving fatigue resistance of joints

To study the effect of MX-4AD and LB-3AD on the improvement of the fatigue resistance, T-shaped fillet joints as shown in Fig. 5 were prepared in a manner similar to that described in the previous section. The MX-200 was used for the main beads, while the newly developed LTT welding consumables were used for the additional weld. The joints thus prepared were subjected to the measurements of residual stress at their weld toes and to the three-point bending fatigue test. For comparison, a T-shaped fillet joint prepared using MX-200 was used as a test joint with its weld toe processed by peening, and another joint prepared in the same manner was used as a test joint with its weld toes ground to smooth surfaces. Here, the pin-tip radius for the peening was 2.5 mm, and the weld toe radius after the grinding finish was 4.5 mm. The appearances of these weld toes are shown in **Fig.11**.

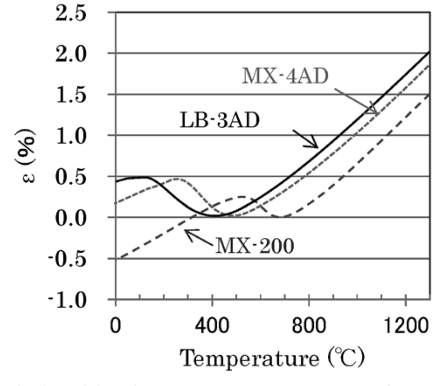


Fig.10 Relationships between temperature and expansion of developed welding consumables

Fig.12 shows the results of the residual stress measurement. Comparing the residual stresses at the weld toes of beads, the T-shaped fillet joint with the main beads consisting only of MX-200 exhibits a tensile residual stress, while the ones with additional welds made of the newly developed LTT welding consumables exhibit large compressive residual stresses. Furthermore, the LB-3AD exhibits compressive residual stress significantly increased by the peening in the immediate vicinity of the weld toe.

Fig.13 summarizes the effect of each process on the improvement of fatigue resistance. The MX-4AD brings about an improvement that almost equals that achieved by a grinding finish. Thus it is expected that replacing the grinding work, which is extremely low in efficiency, with additional welding using the MX-4AD will shorten the work time. The LB-3AD, on the other hand, almost doubles the fatigue life compared with peening and is expected not only to shorten the work time, but also to improve fatigue

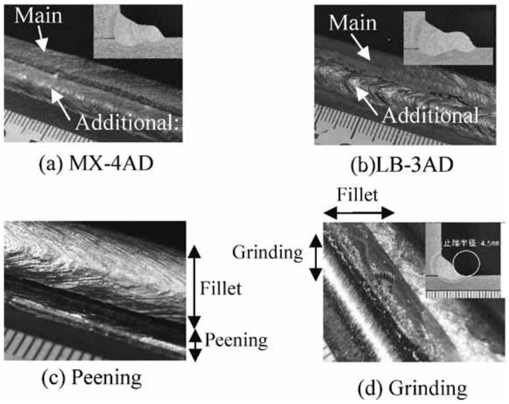


Fig.11 Bead appearance after each treatment

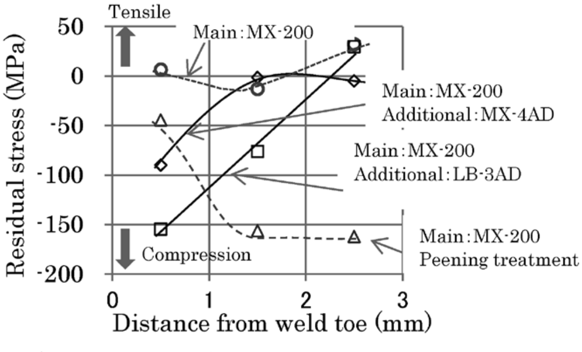


Fig.12 Comparison of residual stresses near weld toes of main beads made of various welding consumables

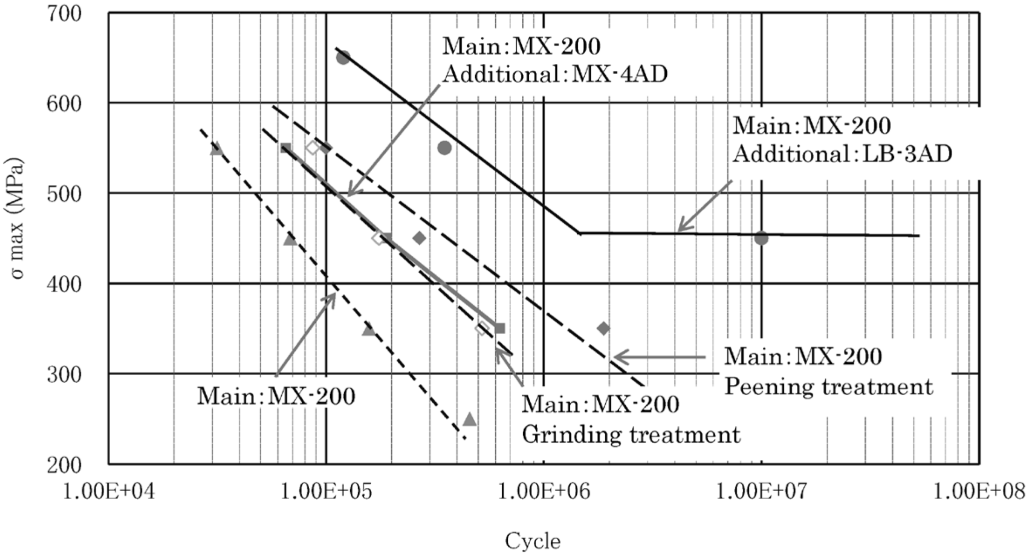


Fig.13 Comparison of bending fatigue strength of each treatment

resistance much more significantly than the current methods.

Conclusions

A study was conducted on the positive addition of Mn to develop new LTT welding consumables, and its effect was confirmed in this paper. The study has led to the manufacturing of two welding consumables, MX-4AD and LB-3AD, for additional welding to improve fatigue resistance. These consumables are advantageous in that the MX-4AD can replace the grinding finish and shorten the work time, while, the LB-3AD can improve fatigue resistance significantly and extend the life of structures better than conventional processes.

Kobe Steel will strive to promote the implementation of these welding consumables and to exploit its own welding consumables and welding system to contribute to the provision of a safe and secure social infrastructure.

References

1) T. Nose. *Journal of the Japan Welding Society (Journal of JWS)*. 2008, Vol.77, No.3, pp.6-9.
2) M. Nishio et al. *the Japan Society of Civil Engineers, The 68th Annual Conference Abstracts 2013-9-4/6*. 2013, pp.1109-1110.
3) C. Miki et al. *Journal of Japan Society of Civil Engineering*. 2002, No.710/I-60, pp.311-319.
4) T. Tominaga et al. *Journal of Japan Society of Civil Engineering*. 2010, Vol.66, No.4, pp.653-662.
5) Y. Ippongi et al. *Bulletin of the Kyushu Institute of Technology*. Science and technology 53, 93-98, 1986-09.
6) T. Kasuya. *Welding Technology*. 2014, Oct, pp.45-49.
7) Japan Road Association. *Specifications for Highway Bridges Commentary*. 2012, pp.200-206.