FATIGUE STRENGTH OF TRANSVERSE ATTACHMENT JOINTS WITH SINGLE-SIDED WELD USING LOW TRANSFORMATION TEMPERATURE WELDING CONSUMABLE

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This study investigated the applicability of low transformation temperature (LTT) consumables to improve fatigue strength against weld root failure. Transverse attachment joints formed by single-sided welding, similar to rib-to-deck connections in orthotropic steel bridge decks, were fabricated using an LTT welding consumable and conventional welding consumable. Fatigue tests were performed with out-of-plane bending loads using a vibration-type fatigue testing machine. The test results indicated that higher fatigue strength can be achieved in the joint with an LTT consumable compared with a conventional one. In addition, residual stresses around the weld bead were clarified by X-ray diffraction measurements and finite element analyses. The results revealed that the LTT consumable can reduce residual stress around the weld and also introduce compressive residual stress to the weld root, which can contribute to improved fatigue strength.

1. INTRODUCTION

Fatigue cracks are likely to occur at weld toes and roots in welded joints because the stress concentration is high and tensile residual stress is introduced by the welding process. This study focuses on root cracks, specifically in orthotropic steel bridge decks, that form in welded joints between a trapezoidal rib and deck plate and then propagate into the deck plate [1, 2]. One potential technique for improving fatigue strength against root failure is to release tensile residual stress at the

weld root, such as by using post-weld heat treatment [3]. Heat treatment with a sheet-type portable heater can reduce the residual stress around such rib-to-deck welds. However, this method requires additional work and cost after welding is complete, and it is difficult to apply to all the welds over an entire steel deck.

Utilization of a newly developed welding consumable, known as low transformation temperature (LTT) welding consumable, is one way to reduce the welding residual stress [4]. The LTT consumable has the characteristic of undergoing austenite to martensite phase transformation near room temperature, which can reduce tensile residual stress and, in some cases, introduce compressive residual stress around the weld without post-weld treatment.

Previous research has reported the reduction of tensile residual stress around welds by using LTT consumables as compared to conventional consumables [4-13]. Fatigue tests have been carried out on several types of welded joints that mainly fail in the weld toe, such as out-of-plane gusset joints [4, 6, 8-11], corner joints [5], lap joints [7], and butt joints [8, 11], and revealed the improvement of fatigue strength in the joint welded with LTT consumables, regardless of the joint type. Other uses of LTT consumables in additional welding applications have been examined [12, 13]. It has been revealed that fatigue strength was improved by adding a weld bead with LTT consumables to an original box weld with conventional consumables. The fatigue strength improvement by using an LTT consumable, however, has been mainly studied for weld toe failure. The applicability of LTT consumables to weld root failure has not been well investigated.

This study focused on the weld root failure observed in rib-to-deck welds of orthotropic steel bridge decks. The improvement of fatigue strength by using an LTT welding consumable was investigated through fatigue tests, residual stress measurements, and finite element (FE) analyses.

2. SPECIMENS
2.1 Specimen Fabrication
Transverse attachment joints formed by single-sided welding, similar to rib-to-deck connections in orthotropic steel bridge decks, were fabricated using LTT and conventional welding consumables. Configurations and dimensions of the specimens are shown in Fig. 1. The mechanical properties and chemical compositions of the steel used in the specimens are listed in Table 1. The main plate and rib plate were 12 and 6 mm in thickness, respectively. The specimen width was 300 mm, and the rib plate was connected to the main plate at an angle of 77°, consistent with the typical configuration of rib-to-deck connections.

Single-side welding with a partial joint penetration groove weld was applied to the specimens. CO_2 gas-shielded arc welding with an LTT wire 1.2 mm in diameter (JIS Z 3313 T780T1-0CA-G) and a conventional wire 1.4 mm in diameter (JIS Z 3313 T49J0T1-0CA-U) was used to fabricate the specimens. Table 1 lists the mechanical properties and chemical compositions of the welding consumables. Welding conditions were set to achieve a weld penetration depth of more than 75% of the rib thickness (t_r), which is the requirement for rib-to-deck joints in the specifications for highway bridges in Japan [14]. Table 2 gives the welding conditions. The specimens were fabricated with both the main and rib plates restrained to a fix angle, and the main plate was positioned horizontally during welding. Macrographs of the welds with the LTT and conventional consumables are shown in Fig. 2. No weld cracking was observed in any specimen. The weld toe in the specimen with the conventional consumable was finished by grinding to ensure the formation of root cracks, while the specimen with the LTT consumable was tested in its as-welded condition.
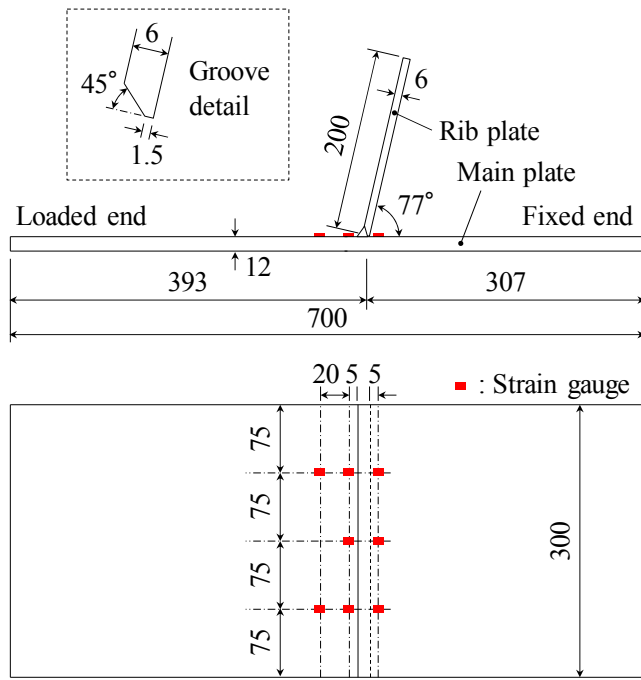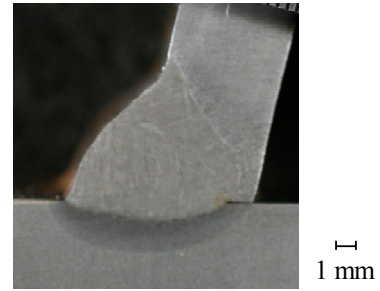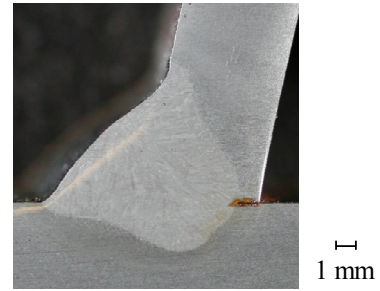
Fig. 1 Specimens (units: mm)

(a) LTT consumable

(b) Conventional consumable

Fig. 2 Macrographs of specimens

Table 1 Mechanical properties and chemical compositions of materials

(a) Mechanical properties

Materials		Yield strength (N/mm²)	Tensile strength (N/mm²)	Elongation (%)
Steel	Main plate	319	439	31
	Rib plate	289	441	27
Welding consumable	LTT	760	811	20
	Conventional	478	572	26

(b) Chemical compositions (%)

Materials		C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V
Steel	Main plate	0.17	0.09	0.60	0.014	0.004	-	-	-	-	-
	Rib plate	0.16	0.02	0.52	0.016	0.006	-	-	-	-	-
Welding consumable	LTT	0.03	0.42	4.6	0.008	0.007	0.01	0.01	0.02	0.01	0.01
	Conventional	0.03	0.47	1.53	0.009	0.008	0.01	0.01	0.02	<0.01	0.01

Table 2 Welding conditions

Welding consumable	Current (A)	Voltage (V)	Welding speed (mm/min)	Heat input (J/mm)	Preheating (°C)
LTT	250	28	370	1,135	50
Conventional	285	26.5	400	1,133	None

2.2 Measurements of Weld Bead Profile

Weld bead profiles consisting of weld leg length (L_M, L_R), weld penetration depth (p), toe radius (ρ), and toe angle (θ), as defined in Fig. 3, were measured for each specimen. The measurements of the weld leg length, toe radius, and toe angle were performed using a replica method. Silicon replicas of weld beads were sliced, and then a profile of each sample was measured by image analysis. The weld penetration depth was determined indirectly by measuring weld root size from fracture surface observations of the specimen.

The averages of the measurements are summarized in Table 3, and the distributions of toe radius and angle are shown in Fig. 4. The toe radius and angle were distributed in a nearly similar region between the LTT and conventional specimens. In addition, the weld leg length and weld penetration depth of the LTT specimen were also approximately equal to those of the conventional specimen.
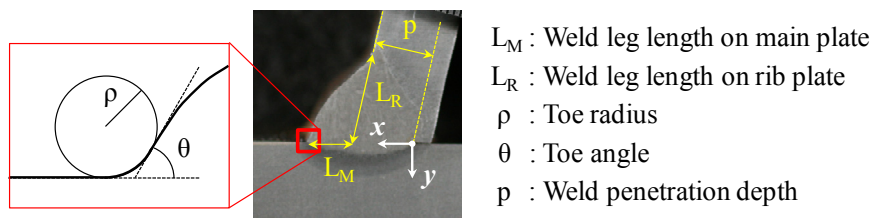

L_M : Weld leg length on main plate
L_R : Weld leg length on rib plate
ρ : Toe radius
θ : Toe angle
p : Weld penetration depth

Fig. 3 Definition of weld bead profile

Table 3 Measurement results of weld bead profile

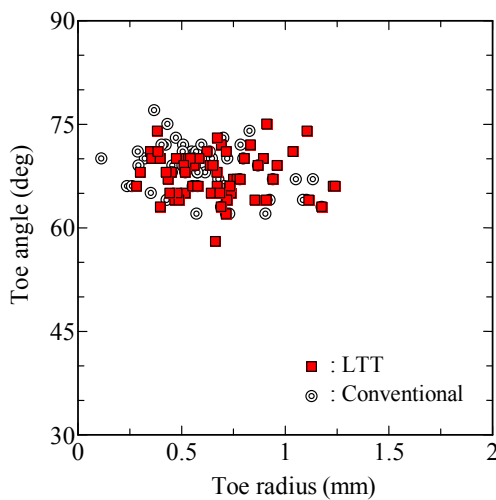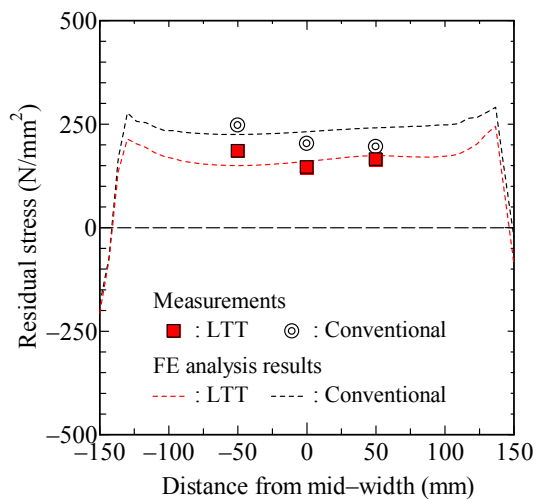| Welding consumable	Leg length		Toe radius	Toe angle	Weld penetration	
	Main plate	Rib plate			Depth	Ratio
	L_M (mm)	L_R (mm)	ρ (mm)	θ (°)	p (mm)	p/t_r
LTT	3.84	7.18	0.62	68.1	4.88	0.81
Conventional	3.87	7.41	0.67	67.7	4.75	0.79

Fig. 4 Weld toe geometry

Fig. 5 Residual stress distributions in transverse direction

2.3 Residual Stress Measurements

Residual stresses near the weld toe were measured with the X-ray diffraction method (iXRD, PROTO Manufacturing) in both the LTT and conventional specimens. The direction of the residual stress was perpendicular to the weld. The spot diameter of the X-ray beam was 1 mm. The residual stress was measured at 2 mm from the weld toe after electropolishing of the specimen surface.

Fig. 5 shows the residual stress distribution in the transverse direction. In the graph, analysis results detailed later are also shown with broken lines for comparison. The ordinate represents the residual stress, and the abscissa represents the transverse distance from the center of the plate width. The specimen with the LTT consumable has residual stresses slightly smaller than those of the specimen with the conventional consumable. Their differences, however, are not significantly large at 2 mm from the weld toe.

3. FATIGUE TESTS

3.1 Loading Method

The specimen was tested under cyclic bending loads. A fatigue testing machine that generates out-of-plane bending deformation to the main plate [15] was used for the fatigue tests. A schematic depiction of the testing system is shown in Fig. 6. One end of the main plate of the specimen was fixed on a supporting column and the other, unsupported end was subjected to cyclic loading by a vibration motor with an eccentric mass. Two stationary springs were affixed to the unsupported end of the specimen to introduce a mean load into the specimen and change the stress ratio. The test was performed under a pulsating load with constant stress amplitude. The stress ratio at the weld was zero. The spring stiffness was set to maintain the mean stress during loading. The frequency of sinusoidal loading ranged from 12.9 to 16.7 Hz.

As shown in Fig. 1, strain gauges were placed on the main plate to monitor the stress range during the test. The nominal stress range of the specimen was determined by linearly interpolating the fluctuation ranges measured by each strain gauge to the weld root. The number of cycles when a strain range monitored by the gauge during the test dropped by 5% is denoted N_5. The N_5 condition is considered to be equivalent to the number of cycles when small cracks occur from the weld root. The fatigue life of the specimen, denoted N_f, was defined as the number of cycles until the specimen ruptured. Cyclic loading was continued with an increased stress range when the specimen did not fail before 10 million cycles.
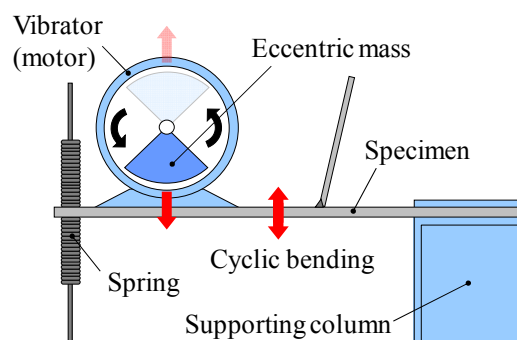


Fig. 6 Fatigue testing machine

3.2 Fatigue Crack Observations

Figure 7 shows fracture surfaces of the specimens with LTT and conventional consumables. A crack grew from the weld root into the main plate in all specimens. Based on a beach mark applied at the N_5 condition in the conventional specimen, the crack length and depth at the N_5 condition were approximately 130.1 mm and 2.58 mm, respectively, which almost corresponds to the tendency obtained in the previous study [16].

3.3 Fatigue Lives

Fatigue test results are summarized in Table 4 and shown in Fig. 8, together with the results with conventional welding consumables obtained by the same testing system [16, 17]. In the graphs, the fatigue design curves specified by the Japanese Society of Steel Construction (JSSC) [18] are also shown. The values in parentheses represent the fatigue strength required at 2 million cycles for each category.

The specimen with the LTT consumable had a fatigue strength higher than that with a conventional consumable. Moreover, slopes of the fatigue strength tend to be different between the LTT and conventional consumables, and the fatigue limit tends to be improved by using the LTT consumable. This demonstrated that the LTT consumable can have beneficial effects on the fatigue strength of rib-to-deck joints in the weld root failure mode.
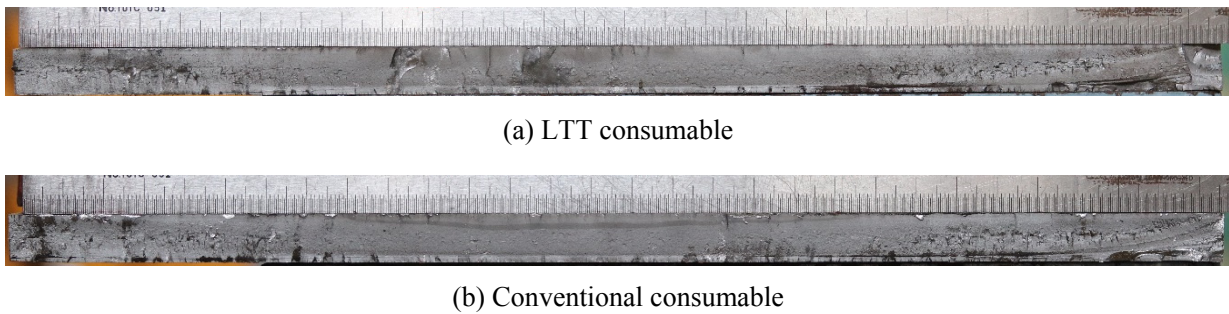
(a) LTT consumable

(b) Conventional consumable

Fig. 7 Fracture surfaces
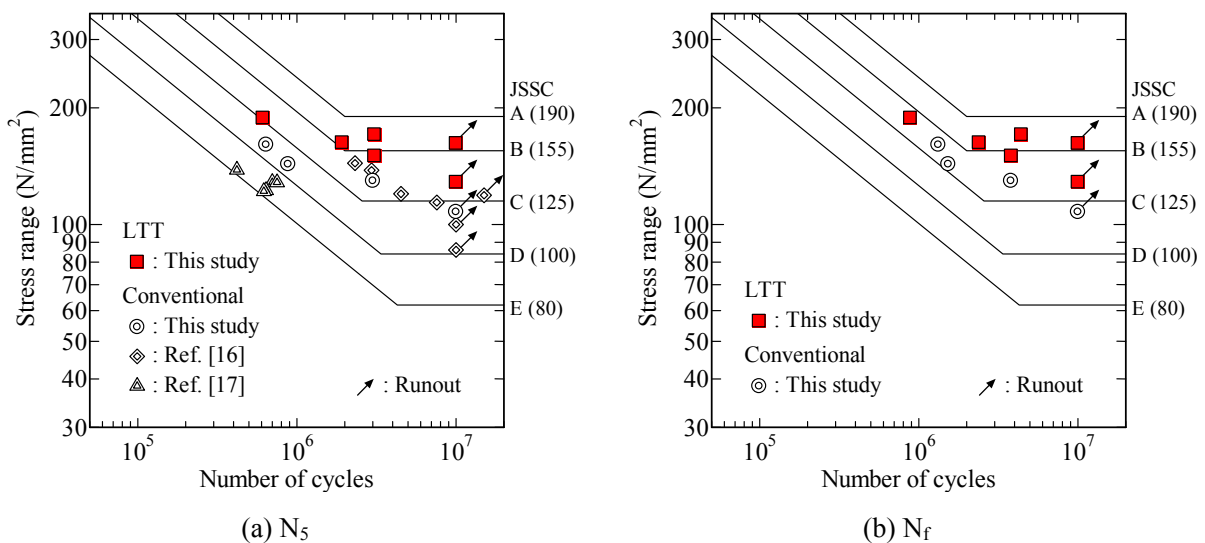
(a) N_5 (b) N_f

Fig. 8 Fatigue test results

Table 4 Summary of fatigue tests

Welding consumable		Stress range (N/mm²)	N_5 (× 10³ cycles)	N_f (× 10³ cycles)	Notes
LTT	L1	128.7	-	> 10,000	Runout
	L1R	150.4	3,070	3,810	Retest of L1 with increased stress range
	L2	162.0	-	> 10,000	Runout
	L2R	170.7	3,070	4,700	Retest of L2 with increased stress range
	L3	162.8	1,920	2,990	
	L4	188.5	610	883	
Conventional	C1	107.9	-	>10,000	Runout
	C1R	129.8	3,000	3,790	Retest of C1 with increased stress range
	C2	143.3	880	1,530	
	C3	160.8	640	1,325	

4. THERMAL ELASTO-PLASTIC FINITE ELEMENT ANALYSIS

Thermal elasto-plastic FE analysis was carried out to clarify residual stress distributions around the weld using LTT and conventional welding consumables.

4.1 Analysis Method

Abaqus ver. 6.14 was used for the analysis, and the FE model is shown in Fig. 9. The boundary conditions were same as the conditions under which the specimens were fabricated. As shown in Fig. 10, the temperature dependence of material properties in the specimen was determined based on a previous study [19].

The phase transformation of the LTT weld metal was expressed by applying the temperature dependency to a coefficient of thermal expansion as shown in Fig. 10(c). The coefficient of thermal expansion for the LTT was taken from a test for determining the transformation temperature. In contrast, the conventional weld metal and steel material were assumed to have a constant thermal expansion. Fig. 11 compares the relationship between temperature and thermal strain in the LTT weld metal. It was confirmed that the phase transformation behavior of the LTT metal is properly simulated by the analysis.

Welding simulation was performed using the element birth and death technique. In this method, weld-line elements are deactivated at an initial state and then reactivated and heated sequentially during the welding process. Heat input and welding speed were based on the specimen welding conditions. Thermal efficiency was set to be 65% in both the LTT and conventional models. The initial ambient temperature was 34 °C. After welding, the model was cooled to room temperature.

4.2 Comparisons of Temperature Histories

Temperature histories obtained in the analysis were compared with those measured during specimen fabrication. A comparison is shown in Fig. 12. Temperature measurements were performed at 5 points on the specimen surface, as shown in the figure. The analysis results correspond well with the measurements, indicating the validity of the FE models.
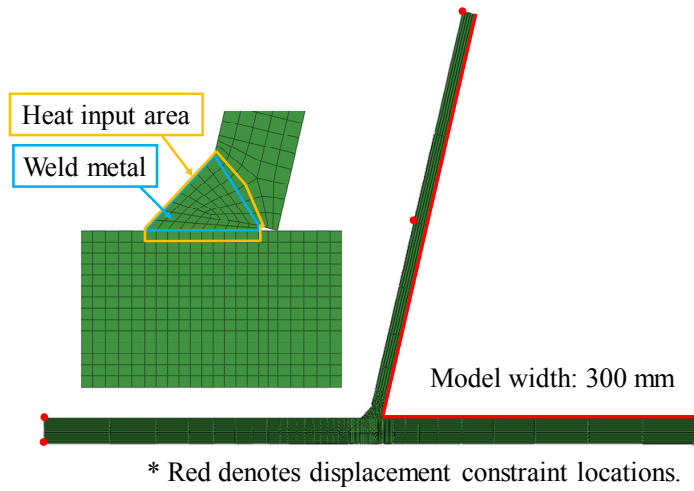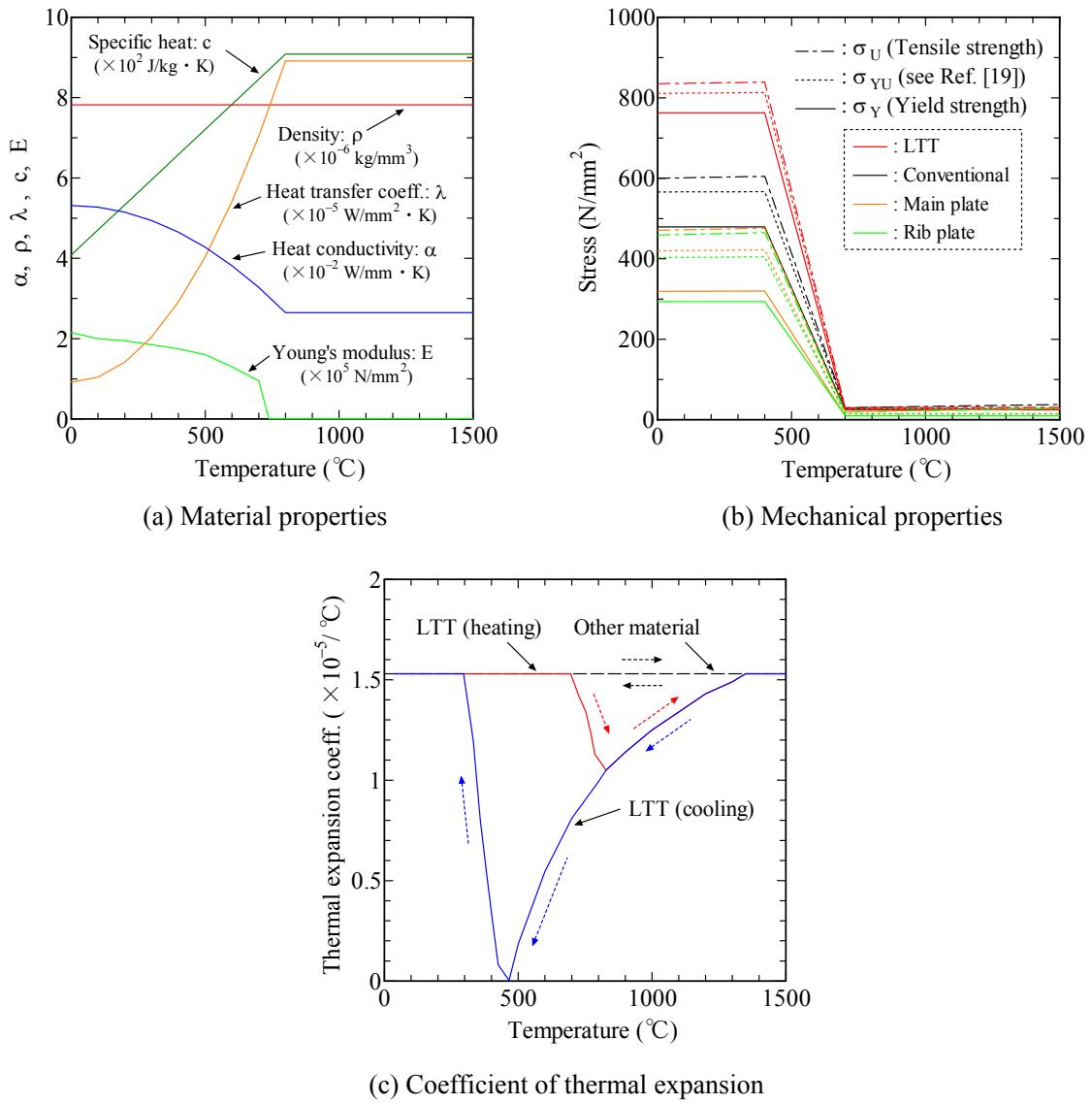
Fig. 9 FE model

(a) Material properties

(b) Mechanical properties

(c) Coefficient of thermal expansion

Fig. 10 Temperature dependency of material properties in FE model
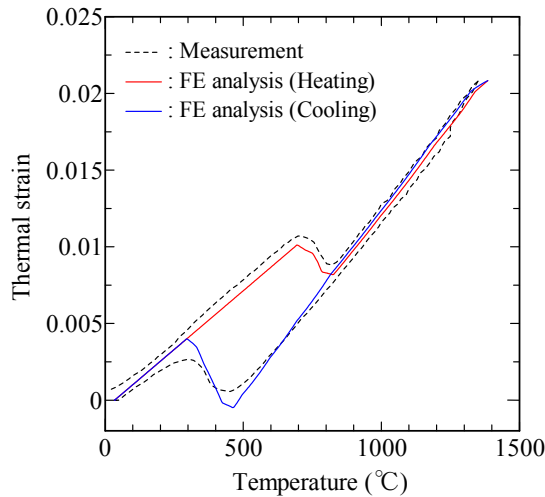
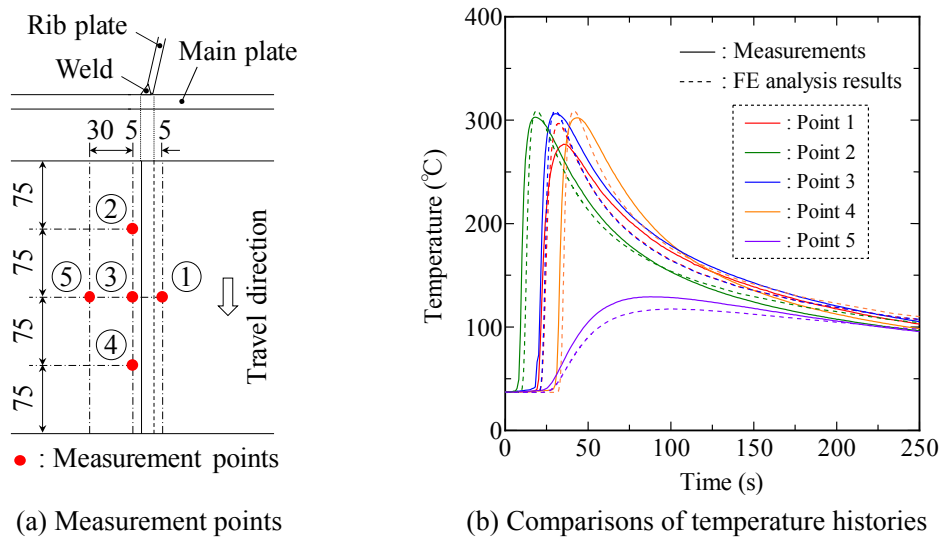Fig. 11 Relationship between temperature and thermal strain in LTT weld metal

(a) Measurement points

(b) Comparisons of temperature histories

Fig. 12 Temperature histories

4.3 Residual Stress Distributions

Figure 5 compares the residual stress distributions from the FE analysis and measurements using the X-ray diffraction method. The distributions are in relatively good agreement.

Simulated residual stress distributions at the center of the plate width are shown in Fig. 13. The direction of the residual stress was perpendicular to the weld. The abscissa in Fig. 13(a) and the ordinate in Fig. 13(b) refer to the distance from the weld root following the x-y coordinate system shown in Fig. 3. Here, the x-axis means the longitudinal direction, and the y-axis means the thickness direction. The residual stress around the weld in the model with the LTT consumable is lower than that with the conventional consumable. Moreover, the LTT can introduce a compressive residual stress to the weld root and toe, which is consistent with the improvement of fatigue strength observed in the fatigue tests.
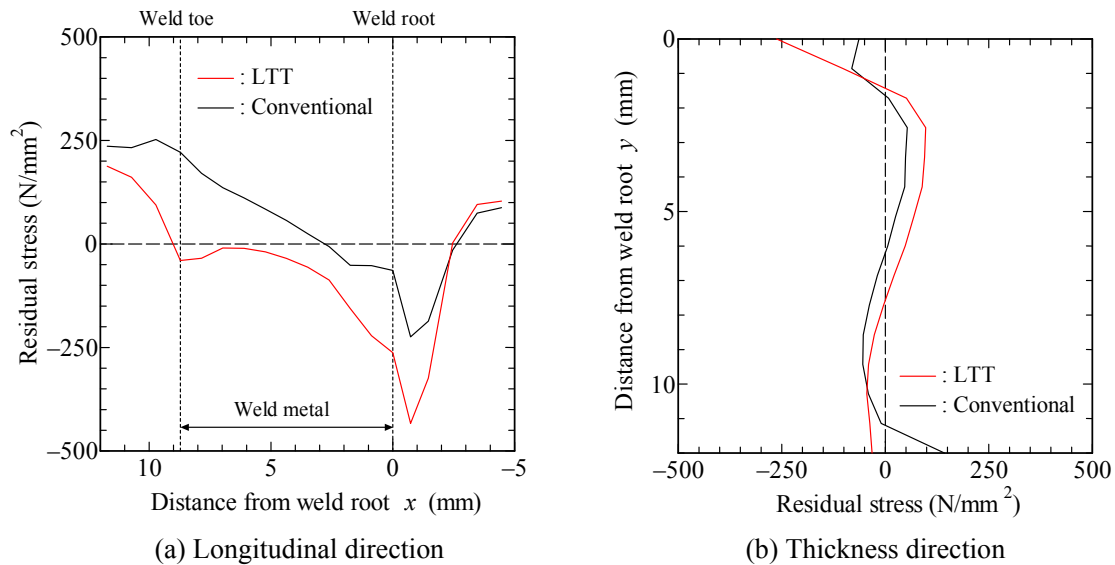
Fig. 13 Comparisons of residual stress distributions obtained from FE analysis

5. CONCLUSIONS

This study investigated the applicability of LTT welding consumables for improving fatigue strength against weld root failure in the rib-to-deck connections of orthotropic steel bridge decks. Fatigue tests and thermal elasto-plastic FE analyses were carried out using transverse attachment joints formed by single-sided welding with LTT and conventional consumables. The results obtained in this study are summarized as follows:

- Similar weld leg length and weld toe geometry were achieved in the specimens with the LTT and conventional consumables.
- The specimens formed with the LTT consumable tended to have higher fatigue strength and fatigue limit than those formed with the conventional consumable.
- Residual stress around the weld was reduced by using the LTT consumable compared with the conventional consumable.
- The analysis results revealed that compressive residual stress can be introduced at the weld root and toe in the model with the LTT consumable, supporting the improvement of fatigue strength in the test.

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