FATIGUE STRENGTH OF ONESIDE-WELDED JOINT WITH BACKING STRIP

By Dong Uk LEE* and Kohsuke HORIKAWA**

Angular distortion and misalignment are the typical initial imperfections of welded-joint in steel structure. Stress and strain concentration at the root and the toe of welded-joint become larger when the welded-joint has misalignment, as misalignment causes a moment with applied force. Therefore, fatigue strength of the welded-joint with misalignment is inferior to that without misalignment.

In this paper, fatigue strength of such joint was investigated using the specimen, which was scale-up model of a cross section of U-shape trough rib. Stress concentration factor of the root was analyzed by the finite-element method and was measured by static loading test. Cyclic loading test was carried out to clarify the effect of root shape on fatigue life and the relation between fatigue crack propagation rate and stress intensity factor range. Also, the effect of scale-up rate of the specimen was investigated.

1. INTRODUCTION

The angular distortion due to thermal cycle as well as misalignment owing to misfitting have been investigated as initial imperfections of welded-joint in steel structure[1]~[4]. It is known that the stress concentration and the strain concentration occur at the root and the toe of welded-joint with angular distortion and misalignment as a moment occurs at the welded-joint with angular distortion and misalignment by applied force[3]~[5]. However, it is hard to avoid misalignments in field-welded joints of steel bridges. Oneside-welded joint with backing strip is often used for the field-welding of a closed U-shape trough rib. Stress flows are disturbed at the welded-joint with backing strip.

According to the results of bending fatigue test on the U-shape trough rib of full scale specimen and tensile fatigue test on specimen with backing strip, where in both cases the specimens included misalignment and weld defects[6],[7] :

1) The fatigue life was shorter as the misaligment became larger,
2) Even though several weld defects were involved in the fusion zone, they were not always crack initiation points,
3) The cracks of all specimens initiated from the root or the toe of welded-joint.

Even the welded-joints were fabricated with same materials and welding conditions, the shapes of the root had various types[7]. It has been known that fatigue life becomes longer when the toe of welded-joint becomes smooth.

This paper deals with stress concentration factor (SCF) and fatigue life of oneside-welded joint with

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backing strip. Specimen was scale-up model of a cross section of a U-shape trough rib with misalignment[6,7]. The root shapes are two types : one is right angle, and the other is semicircular. The SCF was analyzed by the finite-element method and was measured by static loading test. The cyclic loading test was carried out to investigate the effect of root shape on fatigue life and the relation between fatigue crack propagation rate and stress intensity factor range[8,9]. Also, the effect of scale-up rate of the specimen was investigated.

2. ANALYSIS BY FINITE-ELEMENT METHOD

The models were same as experimental specimens which were scale-up models of a cross section of a U-shape trough ribs with misalignment (0, 2, and 4 mm). Configurations and sizes of the specimens are shown in **Fig. 1** and Table 1. The misalignment of the specimen A, B and C are 0, 2 and 4mm respectively. The root shape of specimen B-5 R and C-5 R are semicircular and the others are right angle as shown in **Fig. 1**. The FEM mesh of each specimen is shown in **Fig. 2**. The hatched area R and T in Fig. 2 a) correspond to the root and the toe of welded-joint respectively. **Fig. 2** b~h) indicate the root, and i~j) present the toe. The smallest element size, number of element and nodal point of each specimen are shown in **Table 2**. Nodal points with same coordinates are given individually for each side of contact surface between base metal and backing strip.

Principal stresses on the root and the toe of each specimen were shown in **Fig. 2** b~j) when such external force was applied that nominal stress at parallel portion become unit (1.0 kg/mm^2). Accordingly, the principal stresses correspond to the stress concentration factors (SCF's). From this analysis :

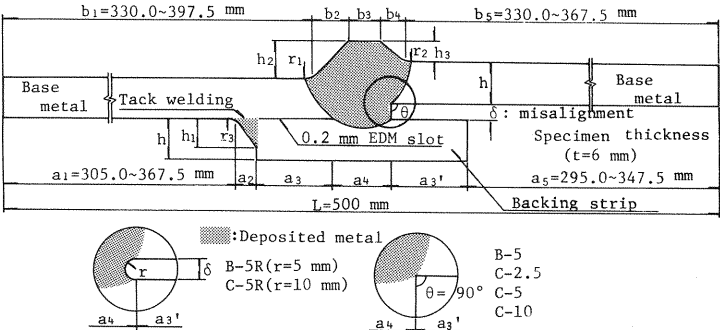1) The SCF was large at base metal side in the root of specimen with right angle, while the SCF was

Fig. 1 Specimen configuration

Table 1 FEM model and test specimen size.   (Unit : mm)

SP.	a_2	a_3	a_3'	a_4	b_2	b_3	b_4	h	h_1	h_2	h_3	r_1	r_2	r_3	δ
A-5	20.0	55.0	55.0	40.0	22.5	25.0	22.5	30.0	20.0	15.0	15.0	20.0	20.0	20.0	0
B-5	20.0	55.0	55.0	40.0	25.0	25.0	20.0	30.0	20.0	25.0	15.0	20.0	20.0	20.0	10.0
B-5R	20.0	55.0	51.1	43.9	25.0	25.0	20.0	30.0	20.0	25.0	15.0	20.0	20.0	20.0	10.0
C-2.5	10.0	27.5	27.5	20.0	11.3	12.5	11.3	15.0	10.0	15.0	5.0	20.0	20.0	20.0	10.0
C-5	20.0	55.0	55.0	40.0	22.5	25.0	22.5	30.0	20.0	30.0	10.0	2.5	10.0	2.5	20.0
C-5R	20.0	55.0	47.2	47.9	22.5	25.0	22.5	30.0	20.0	30.0	10.0	20.0	20.0	20.0	20.0
C-10	40.0	55.0	55.0	40.0	45.0	50.0	45.0	60.0	40.0	60.0	20.0	0	0	0	40.0

Table 2 The smallest element size, number of elements
and nodal points on each specimen.

Specimen	A-5	B-5	B-5R	C-2.5	C-5	C-5R	C-10	C-5R(T)	C-10(T)
S.EL.S	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Element	330	392	392	323	376	379	391	297	346
N.Point	204	234	238	208	226	230	238	194	215

S.EL.S :Smallest Element Size (mm)
Element:Number of Elements
N.Point:Number of Nodal Points
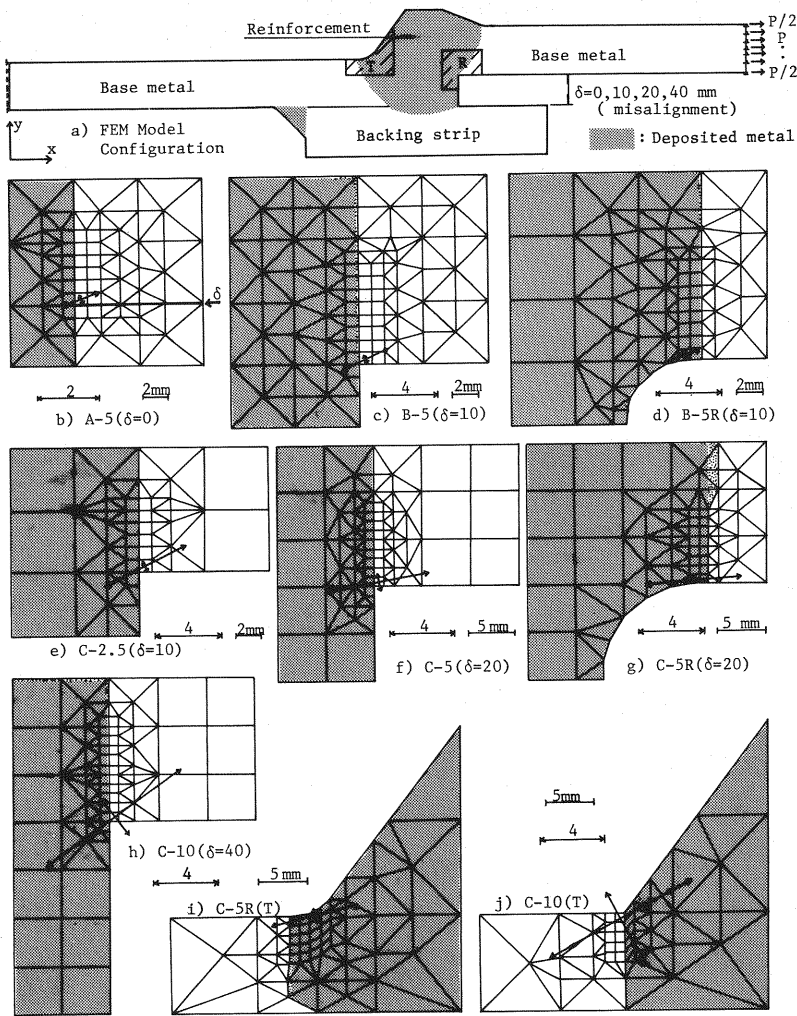
Fig. 2 Stress concentration factor on root and toe of each specimen.

large at deposited metal side in the root of specimen with semi-circular,

2) The SCF of specimen C-10 was large at the toe as well as the root.

3. STATIC TEST

The experimental models are as before-mentioned. The materials of all specimens are mild steel of 400 MPa in tensile strength. Slot shown in **Fig. 1** was cut by Eletro-discharge Machine. **Fig. 3** shows
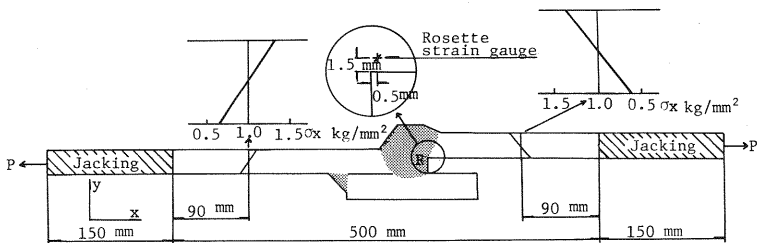

Fig. 3 Stress distribution at parallel portion of specimen C-5.

stress distribution at parallel portion of specimen C-5 when the nominal stress is unit (1.0 kg/mm^2). From the stress distribution shown in **Fig. 3**, the specimen is subject to a moment with applied force due to misalignment. Stress concentration factors (σ_X/σ_{nom} and σ_1/σ_{nom}) at the root of each specimen are shown in **Fig. 4**. Also, the SCF by the finite-element analysis shows in Fig. 4. The stress concentration factors (SCF's) are quantitatively different between the rosette strain gauges and the FEM analysis because the rosette strain gauge can not be attached at edge of specimen. However, the stress concentration factors by the rosette strain gauges and the FEM analysis are qualitatively coincided when misalignment and root radii changed.

Fig. 4   Stress concentration factor on root for misalignment and root radius.

4.   FATIGUE TEST

(1)   Experimental procedure

Specimens were the used tensile test specimens, and crack gauges (pitch 1.0 mm) were attached to both sides of specimens instead of rosette strain gauges shown in **Fig. 3**. The applied stress range was $\Delta\sigma=144$ MPa ($\sigma_{max}=162$ MPa, $\sigma_{min}=18.0$ MPa). Crack propagations were measured and recorded continuously. All tests were carried out under constant stress amplitude of sine wave with servohydraulic testing machine at frequency of 3 Hz.

(2)   Test results

Fractured surface of specimen A-5, B-5, B-5 R, C-5 and C-5 R presented fatigue striation pattern, secondary crack and inter-granular propagation, which are charateristic features of fatigue by constant amplitude cyclic load[10),11]. Crack of specimen C-5 R was initiated from the root at first, and then another crack occured at the toe when the first crack propagated up to 3 or 4 mm. Crack of specimen C-10 was initiated from the toe at first, and the striation pattern was not observed, but fibrous pattern was observed on the fractured surface.

The crack propagation behavior of each specimen was shown in Fig. 5. The figure presented crack initiation life (N_i) and fracture life (N_f). Although the moment due to the misalignment occured at both specimen B-5 R and C-5 R, fatigue lives were longer than the specimen A-5 which had not misalignment as shown in **Fig. 5**. Even though the moment owing to misalignment occured, the fatigue life was improved when the root shape was semicircular.

Fig. 6 shows relation between the fatigue life and the scale-up rate for specimen C-2.5 and C-5 which had the same root shape. The crack initiation life (N_i) was almost constant, but fracture life (N_f) decreases
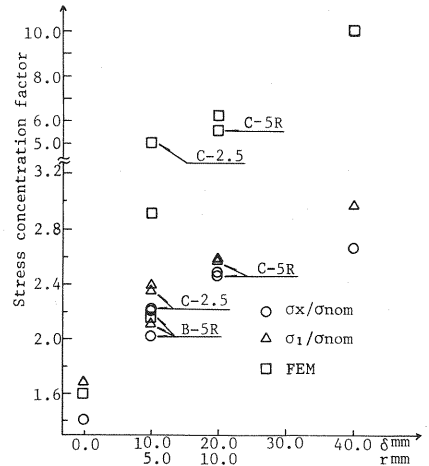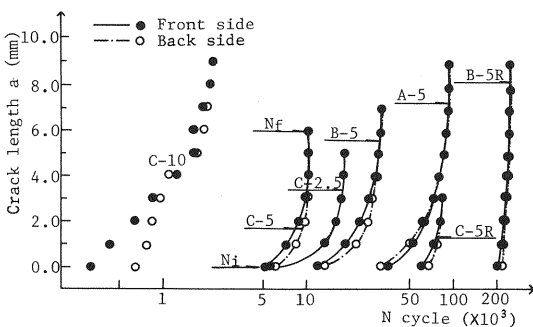

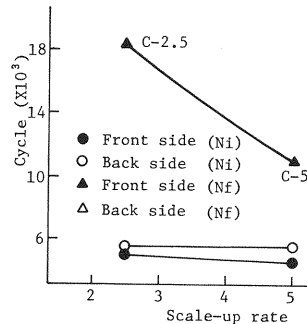Fig. 5   Crack propagation behavior of each specimen.

Fig. 6   Relationship between the fatigue life and the scale-up rate.

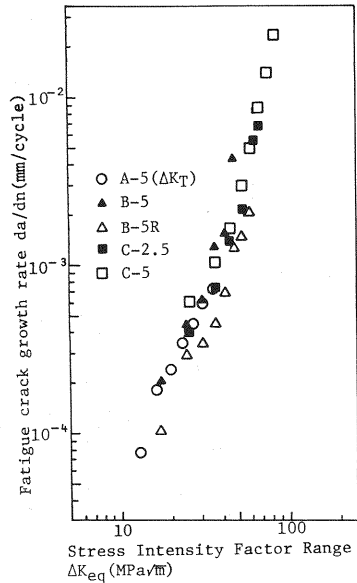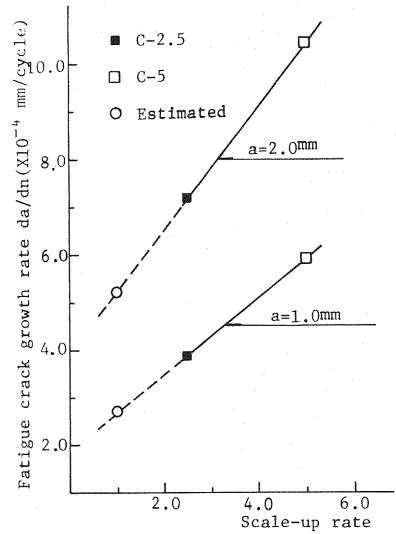Fig. 7 Relation between (da/dn) and (ΔK_{eq}).

Fig. 8 Relation between (da/dn) and scale-up rate.

from 19×10^3 to 12×10^3 when the scale-up rates are changed from 2.5 to 5. This means that crack propagation life (N_p) depends upon the scale-up rate.

(3) Discussions on crack propagation

Neglecting the reinforcement and the backing strip shown in **Fig. 2 a)**, the fracture mechanics is applied on fatigue crack growth rate (da/dn) of each specimen. The stress intensity factor range (ΔK_T) due to tensile stress (σ_t) and the stress intensity factor range (ΔK_B) due to bending stress (σ_b) are given as follows respectively[8),9)].

$$\Delta K_T = \Delta \sigma_t \sqrt{\pi a} \ F(\xi) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where, $F(\xi) = F(a/h) \doteqdot 1.12 - 0.231\ \xi + 10.55\ \xi^2 - 21.72\ \xi^3 + 30.39\ \xi^4$

$\quad\quad a$: crack length, h : specimen width $\quad \Delta K_B = \Delta \sigma_b \sqrt{\pi a}\ F(\xi) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$

where, $F(\xi) \doteqdot 1.122 - 1.40\ \xi + 7.33\ \xi^2 - 13.08\ \xi^3 + 14.04\ \xi^4$

The stress intensity factor range (ΔK_{eq}) of a moment with applied force is assumed as follows.

$$\Delta K_{eq} = \Delta K_T + \Delta K_B \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Fig. 7 shows relation between the fatigue crack growth rate (da/dn) and the stress intensity factor range (ΔK_{eq}) of each specimen. This figure shows that $da/dn \sim \Delta K_{eq}$ relations are rather same even when root shape changed from right angle to semicircular. **Fig. 8** shows relationship between the da/dn and the scale-up rate of specimen C-2.5 and C-5 when crack lengths grew from 1.0 mm to 2.0 mm. In **Fig. 8**, extrapolating the curves to scale-up rate of 1.0, crack growth rate can be read as 2.7×10^{-4} and 5.2×10^{-4} respectively.

5. SUMMARY

The fatigue strength of welded-joint with misalignment was investigated using the specimen which was scale-up model of a cross section of U-shape trough rib. The stress concentration factor of the root was analyzed by the finite-element method and was measured by static loading test. The cyclic loading test was carried out to clarify the effect of root shape on fatigue life, and the relation between fatigue crack propagation rate and stress intensity factor range. Also, the effect of scale-up rate of the specimen was investigated. The major findings can be summarized as follows :

(1) The SCF was large at base metal side in the root of specimen with right angle, while the SCF was

large at deposited metal side in the root of specimen with semicircular, and the SCF of specimen C-10 was large at the toe as well as the root.

(2)   The stress concentration factors (SCF's) were quantitatively different between the rosette strain gauges and the FEM analysis. However, the stress concentration factors by the rosette strain gauges and the FEM analysis were qualitatively coincided when the misalignment and the root radii changed.

(3)   Even though the moment owing to misalignment occured, the fatigue life was improved when the root shape was semicircular.

(4)   Extrapolating the curves to scale-up rate of 1.0, the crack growth rate can be read as 2.7×10^{-4} and 5.2×10^{-4} respectively.

(5)   The configuration had to be changed smoothly at the toe as well as the root because the SCF was fairly large, and also the fatigue crack was initiated from the toe.

The fatigue strength of the welded-joint can be improved with smooth root shape as well as toe shape. For this purpose, such welding techniques are considered as changing angle of welding torch, depositing lesser weld metal with lower welding current and using consumables of higher interfacial tension between molten metal and slag.

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