Fatigue crack propagation behavior of fillet welded joint subjected to bending

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Fatigue tests have been carried out on three types of non load-carrying fillet welded joint subjected plate bending, such as single-side fillet welded joint, T-shaped fillet welded joint and cruciform fillet welded joint. Fatigue failure mode of each type of welded joint has been demonstrated. The test results show that fatigue crack forms flat semi-ellipse during crack propagation and propagates to about 80% of plate thickness before failure. The fatigue strength and life recorded under bending test have been assessed and compared with the previous test results. Moreover, the fatigue strength for bending is evaluated by using one-millimeter stress method.

Key Words: Fatigue crack, fatigue strength, fillet welded joint, bending

1. INTRODUCTION

Fatigue behavior of welded joint subjected to bending has been recognized by several studies. For example, Maddox[1)] provided test results of the welded joints with 11 mm thick plate loaded in bending. He presented the fatigue strength of welded joints that failed at weld toe or root. Miki *et al.*[2)] studied the size effects of plate or rib thickness on the fatigue strength of T-shaped welded joints subjected to bending load by fatigue tests and fatigue crack propagation analysis. Gurney[3)] has investigated the fatigue strength of transverse butt welds in bending. A direct comparison between those results and the results for similar models under axial loading was provided in his study. Fukuoka *et al.*[4)] focused on introducing the fatigue strength of cruciform welded joint with K-butt weld on plates of 25 and 49 mm thickness loaded in bending and fatigue life prediction, which has been performed by using an influence coefficient method. Thus, these tests summarized that bending tests could assure longer fatigue life than tension tests. However, it has been little noted to demonstrate the fatigue crack propagation behavior relating to the fatigue life to failure.

This study aims to investigate fatigue crack propagation and failure correlating with the fatigue strength of fillet welded joint subjected to bending. In particular, the fatigue crack developed at weld toe is examined by carrying out the fatigue test on three types of fillet welded rib to 19 mm thick plate subjected to bending, following the previous fatigue test on fillet welded joint specimens with 12 mm thick plate[5)]. Additionally, the fatigue strength for bending is evaluated by using one-millimeter stress method[6)].

2. FATIGUE TEST

2.1 Test specimens

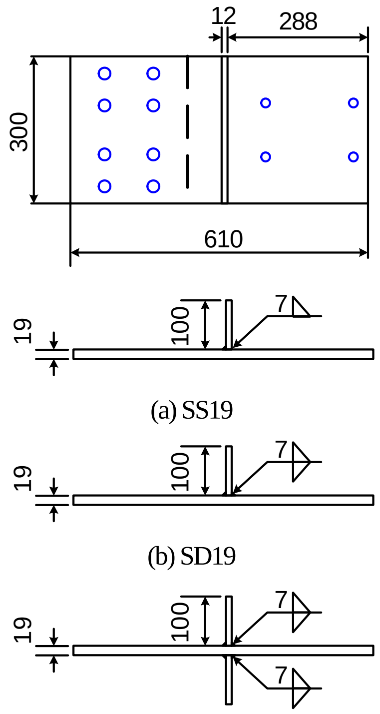
Test specimens are made from 19 mm thick plates of JIS-SM400A. These specimens have fillet welded rib to the structural steel plate of 19 mm thickness and 300 mm width. Details of the specimens are shown in Fig.1. Three types of the specimens are tested. The first one is the single-sided fillet welded joint denoted by SS. The second one is the T-shaped fillet welded joint, denoted by SD, and the last one is the cruciform fillet welded joint, denoted by CR. For all specimens, CO_2 gas shielded arc welding is performed. The mechanical properties and chemical compositions of the steel are given in Table 1.

2.2 Testing condition

The fatigue test is carried out using a fatigue testing machine generating a plate bending type of loading[7)], as shown in Fig.2. A cantilever-type specimen is set first on frame bed and then a vibrator is installed on the plate to generate constant amplitude vibration. The vibration is transformed into a bending type loading to apply to a test specimen. To control stress ratio, *R*, a set of springs is adjusted to a certain desired level. The

Table 1 Mechanical properties and chemical compositions of the steel

t (mm)	Yield stress (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Chemical compositions (%)				
				C	Si	Mn	P	S
19	284	434	32	0.12	0.19	1.03	0.017	0.004



(a) SS19

(b) SD19

(c) CR19

Fig.1 Test specimens

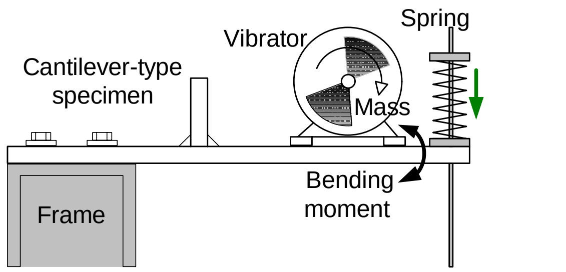


Fig.2 Test set-up

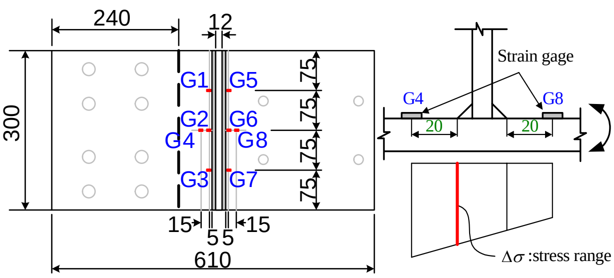


Fig.3 Strain gages location

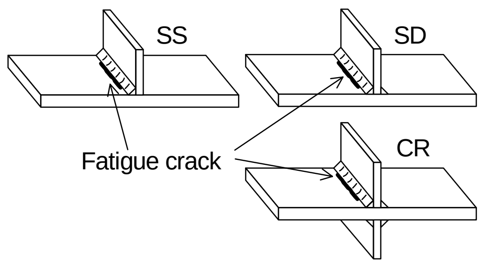


Fig.4 Fatigue crack location

adjustment of these springs produces tensile stress to the specimen surface before this test is conducted under the stress ratio, $R > 0$.

To monitor stress ranges, strain gages are placed 5 mm away from the weld toe, as shown in Fig.3. The strain gages, G4 and G8 at the center of each specimen, are selected as the applied stress range indicator. The strain data measured by G4 and G8 are calibrated by the interpolation procedure to determine the stress range at the weld toe. To detect crack initiation, some copper wires of 0.04 mm in diameter are glued on the surface of weld toe. Dye penetrant and beach mark techniques are applied to shaping crack path on fracture surface.

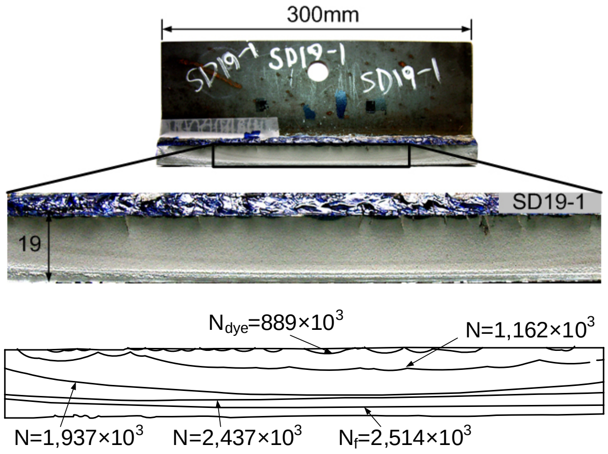
3. TEST RESULTS

3.1 Crack initiation and propagation

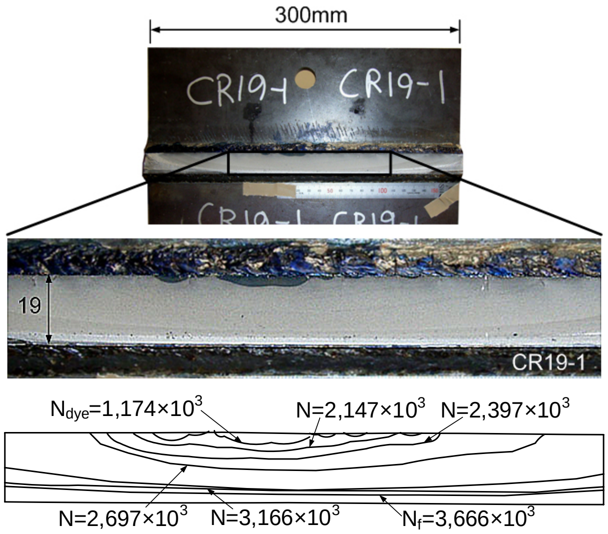
Fatigue crack location is schematically illustrated in Fig.4. Most specimens developed fatigue cracks at weld toe and failed finally. Failure at weld toe is shown in Fig.5(a). Some of SS specimens, however, have weld toe and/or root cracking and their failures are shown in Fig.5(b),(c). Most specimens have fatigue cracks initiated at several points of weld toe, and then coalesced into large semi-elliptical shapes during crack propagation. Finally, these fatigue cracks have propagated to about 80% of plate thickness until failure, which is monitored by

(a) Failure at weld toe (SD19-4) (b) Failure at weld root (SS19-4) (c) Failure at weld toe and root (SS19-2)

Fig.5 Failure modes



(a) SD19-1 specimen



(b) CR19-1 specimen

Fig.6 Fracture surfaces with dyed marks and beach marks

crack initiation at the plate back surface. Some typical fracture surfaces are shown in Fig.6.

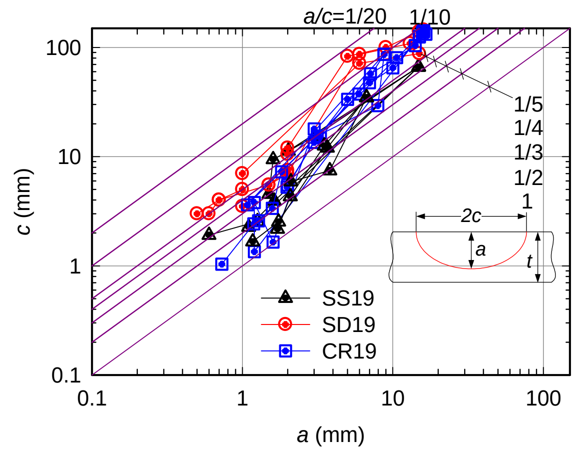


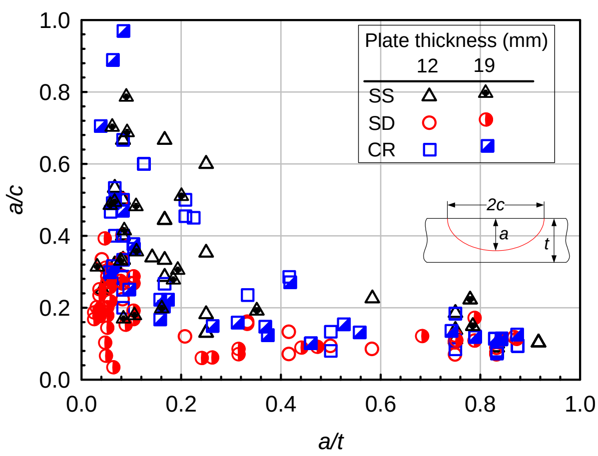
Fig.7 Crack shape development

Crack shapes marked on the fracture surface have been measured and plotted in Fig.7. As can be seen, as crack depth, *a*, grows, crack length, *c*, grows further. This implies that fatigue crack growth rate tends to be faster in the surface direction than in the depth direction. Stress gradient due to bending may delay the crack propagation in the depth direction, while local stress concentration due to weld geometry affects the rapid crack propagation along weld toe in the surface direction.

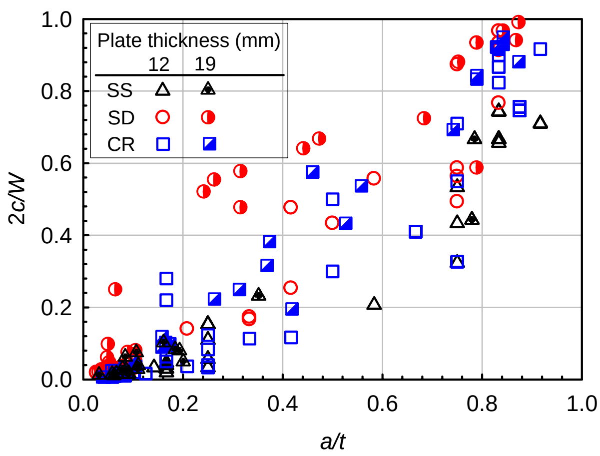
Plotted in Fig.8(a) is variation of aspect ratio, *a/c*, to crack depth ratio, *a/t*, to observe the crack shape change. The previous test results of specimens with 12 mm thick plate[5] are also included. The values of *a/c* decrease at the early stage of crack propagation and maintain lower until failure, because the welded joint specimens have small and multiple cracks coalesced together at an earlier time before forming long and large semi-elliptical cracks. This leads the rapid crack propagation in the surface direction and then the aspect ratio drops off. As *a/t* goes close to 0.8, the crack continues to grow in the surface direction and the value of the crack length to plate width, 2*c/W*, becomes near to 1.0, as shown in Fig.8(b).

3.2 Crack shape variation during propagation

3.3 Fatigue crack propagation life

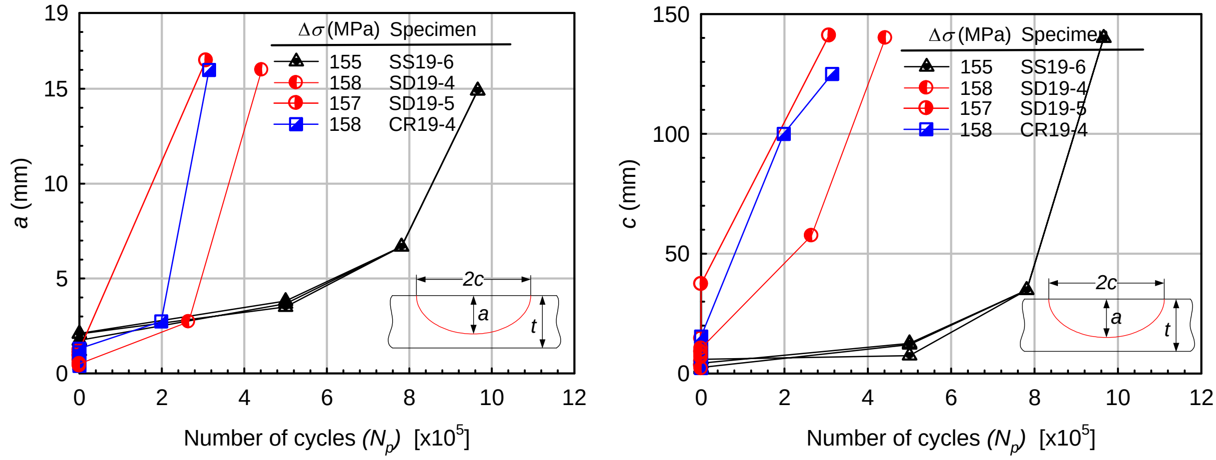


(a) *a/c* vs. *a/t*



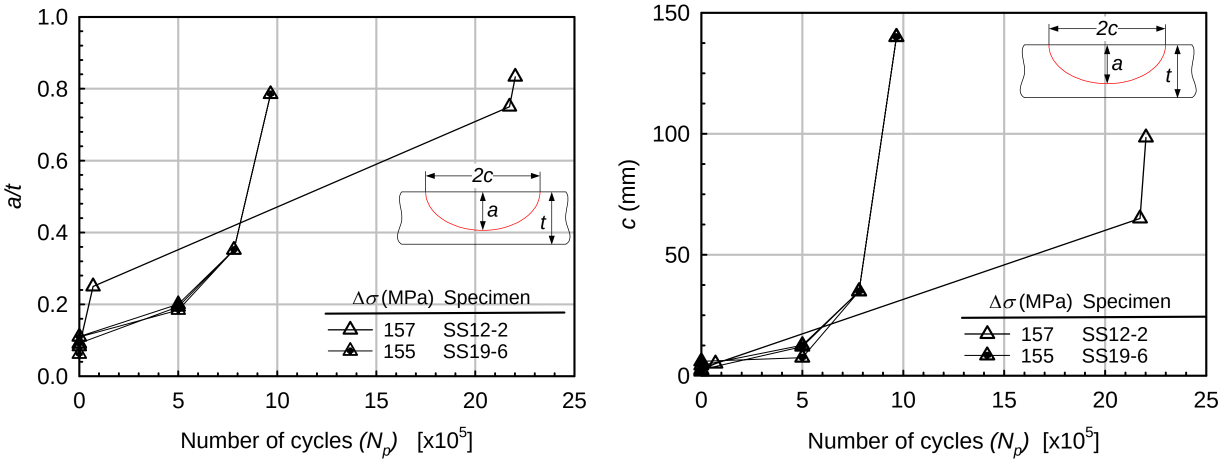
(b) 2*c/W* vs. *a/t*

Fig.8 Aspect ratio, *a/c* and 2*c/W*, to crack depth ratio, *a/t*



(a) Crack depth, *a*, and the number of cycles, N_p (b) Crack length, *c*, and the number of cycles, N_p

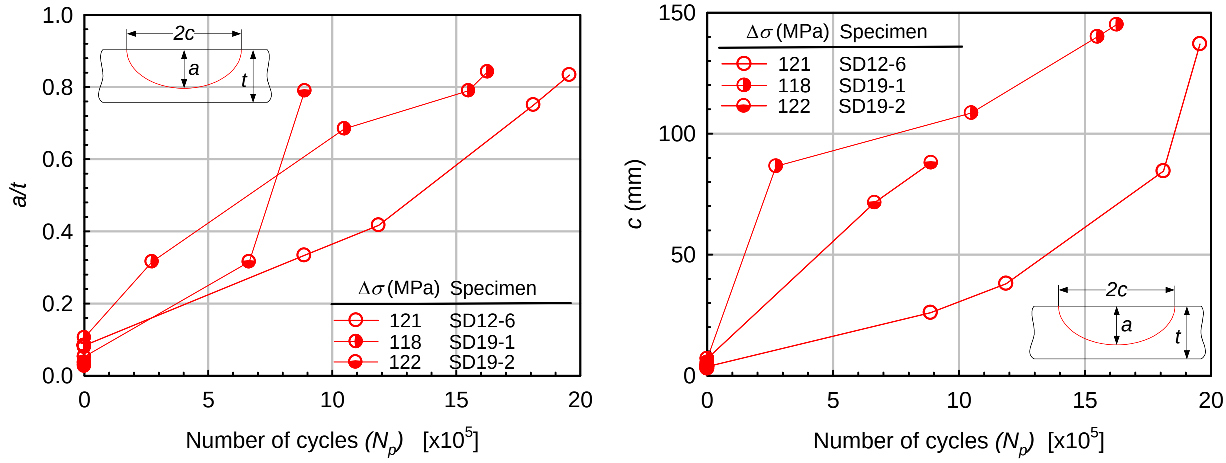
Fig.9 Fatigue crack propagation life of each type specimen



(a) Crack depth to plate thickness, *a/t*, and the number of cycles, N_p

(b) Crack length, *c*, and the number of cycles, N_p

Fig.10 Fatigue crack propagation life of SS19 in comparison with that of SS12

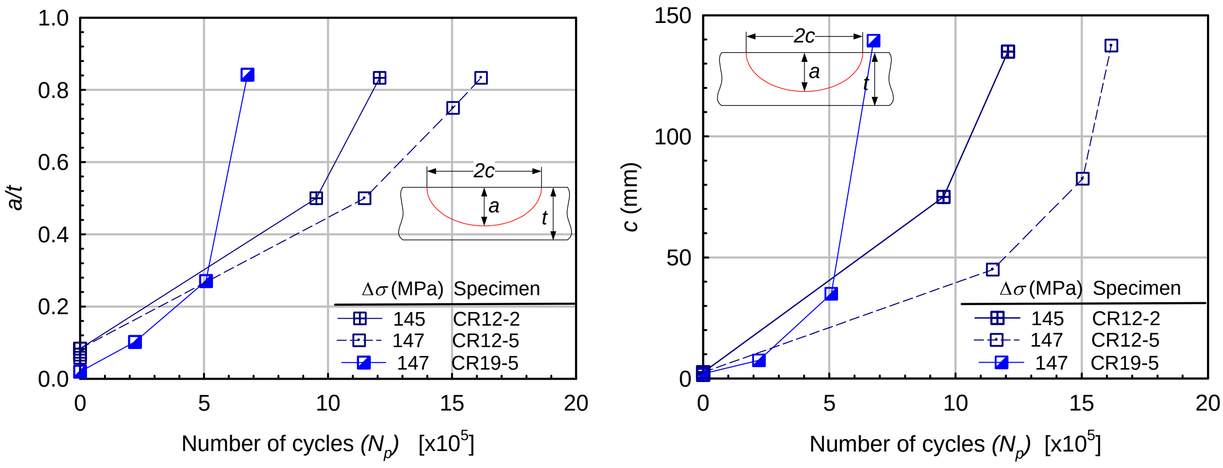


(a) Crack depth to plate thickness, *a/t*, and the number of cycles, N_p

(b) Crack length, *c*, and the number of cycles, N_p

Fig.11 Fatigue crack propagation life of SD19 in comparison with that of SD12

The fatigue crack propagation life of each type of specimen is estimated by using the number of cycles recorded from dye-marking to failure. The number of cycles of when dye-marking has been done is denoted by N_{dye}. The number of cycles to failure is denoted by N_f. Then, the number of cycles of fatigue crack propagation, N_p is calculated in the following form,



(a) Crack depth to plate thickness, a/t, and a number of cycles, N_p

(b) Crack length, c, and a number of cycles, N_p

Fig.12 Fatigue crack propagation life of CR19 in comparison with that of CR12

$$N_p = N_f - N_{dye} \tag{1}$$

Plots in Fig.9 are comparing the measured crack sizes, a, and c, with the number of cycles for the specimens. The fatigue crack propagation life of SD19 is little different from that of CR19. SS19 has longer life than others in the early stage of fatigue crack propagation, but its crack propagation is similar to others when fatigue crack becomes large.

Shown in Fig.10 is the fatigue crack propagation life of SS19 in comparison with that of SS12[5], tested previously. The crack depth is normalized by the plate thickness. As can be seen, the fatigue crack propagation life of SS19 tends to be shorter than that of SS12. The fatigue crack propagation life of SD19 also becomes shorter than that of SD12[5], as shown in Fig.11. The fatigue crack propagation life of CR19 is shorter than that of CR12, as shown in Fig.12.

3.4 Fatigue strength and life

The fatigue test results are listed in Table 2. The fatigue life of failure corresponding to the recorded nominal stress range data are plotted on S-N curve, as shown in Fig.13. Also compared is the design strength for bending specified by JSSC[8], which recommends that fatigue strength for bending be 1.25 times larger than that for tension, in the condition that the plate thickness of welded joint is 25 mm or less. It indicates that as-welded fillet welded joint, such as CR19, with JSSC-E for tension, if under bending, has JSSC-D fatigue resistance. As can be seen, the test results satisfy the design strength for bending.

The regression analyses are conducted for each set of specimens with the inverse of the slope being assumed as m=3 in the following equation,

$$\log N = c - m \times \log \Delta\sigma \tag{2}$$

where N is a number of cycles to failure, and $\Delta\sigma$ is a nominal stress range in MPa. Results of regression analyses for the test results are listed in Table 3. Also listed are the previous test results of specimens with 12 mm thick plate. The standard deviation s is calculated by taking log N as variable, and the

Table 2 Summary of fatigue test results

Type	Specimen	$\Delta\sigma$ (MPa)	N_{dye} ×10^3	N_f ×10^3
Single-sided fillet welded joint	SS19-1*	100	-	>10,000
	SS19-1**	138	-	1,547
	SS19-2	198	321	546
	SS19-3	170	635	1,070
	SS19-4**	138	1,683	3,073
	SS19-5**	161	-	995
	SS19-6	155	1,214	2,180
T-shaped fillet welded joint	SD19-1	118	889	2,514
	SD19-2	122	432	1,321
	SD19-3	104	1,270	2,442
	SD19-4	158	198	640
	SD19-5	157	187	494
	SD19-6	95	1,195	3,519
Cruciform fillet welded joint	CR19-1	110	1,174	3,666
	CR19-2	120	905	2,648
	CR19-3	105	1,978	3,652
	CR19-4	158	311	626
	CR19-5	147	256	931
	CR19-6	101	1,740	3,721

Note: *specimen retested after 10,000×10^3 cycles without any crack being found.
**specimen had weld root failure.

Table 3 Fatigue strength at 2 million cycles

Specimen type	c	s	Mean strength at 2×10^6 cycles (MPa)
SS12	13.1065	0.2826	186
SD12	12.6843	0.1548	134
CR12	12.7877	0.1694	146
SS19	12.7525	0.2032	141
SD19	12.4330	0.1249	111
CR19	12.5704	0.1293	123

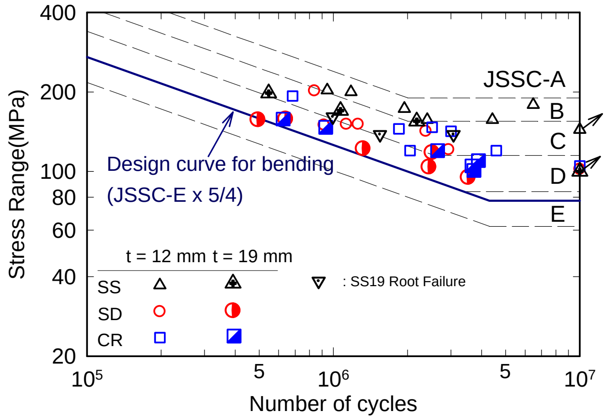


Fig.13 Fatigue test results of fillet welded joint specimens with *t*=12 mm and *t*=19 mm

mean fatigue strength shown in the table is the stress range at 2 million cycles. The run-out data are not included.

As a result, the fatigue strength of SS19 is higher than those of SD19 and CR19. The fatigue strength at 2 million cycles of SS19 is 1.27 and 1.15 times higher than those of SD19 and CR19, respectively. The fatigue strengths at 2 million cycles of SS19, SD19 and CR19 are about 16, 23 and 24% lower than those of SS12, SD12 and CR12.

3.5 Comparison with previous test results

Shown in Fig.14 are the test results of SS19 in comparison with those of SS12. Also added are the previous test results of single-sided fillet welded specimens demonstrating the fatigue behavior of welded joint of trough rib to an orthotropic deck plate[9]. The trough rib type specimen consisted of 6 or 8 mm thick attachment, which is fillet welded at a 78-degree angle to the plate. These specimens have failed by weld toe or root cracking. This figure shows the test results for toe failure of each type of specimen. As can be seen, the fatigue strength of SS12 is little different from that of the trough rib type specimen, because both specimens have almost same dimensions.

The test results of SD19 are plotted with those of SD12 in Fig.15 and compared with the previous test results provided by Mori[10] and Tanaka *et al.*[11]. As can be seen, the test results of both SD12 and SD19 seem lower than their test results[10, 11], in terms of plate thickness. In the previous test results plotted in Fig.15, the data of 9 and 15 mm plate thickness specimens have been distributed obviously larger than the data of 24, 34 and 50 mm plate thickness specimens, but, the data of 12 mm plate thickness specimen, RB[11], seem equivalent to or lower than the data of 15 mm plate thickness specimen, PC15[10]. This may be due to the fact that other size parameters as well as plate thickness are in effect to determine the fatigue strength. According to the previous fatigue test results[6], wider non load-carrying fillet welded joints tend to have lower fatigue strengths. The plate widths of the previous test specimens in Fig.15 are smaller than 130 mm, while all specimens

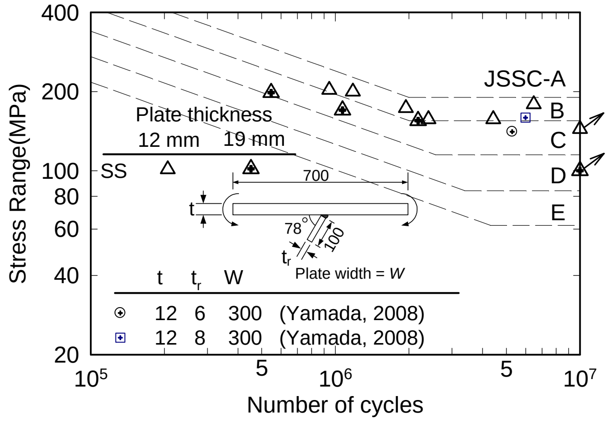


Fig.14 Fatigue test results of SS12, 19 in comparison with the previous test results

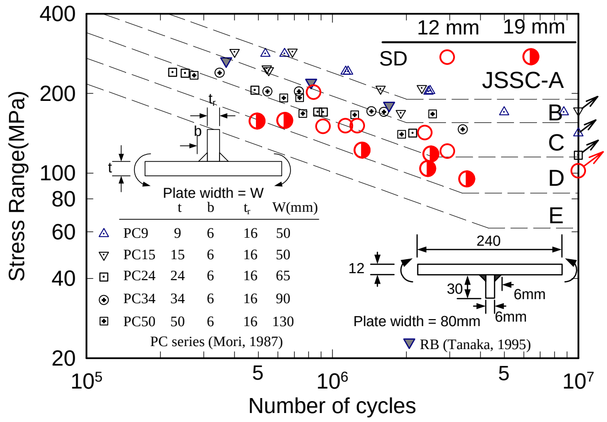


Fig.15 Fatigue test results of SD12, 19 in comparison with the previous test results

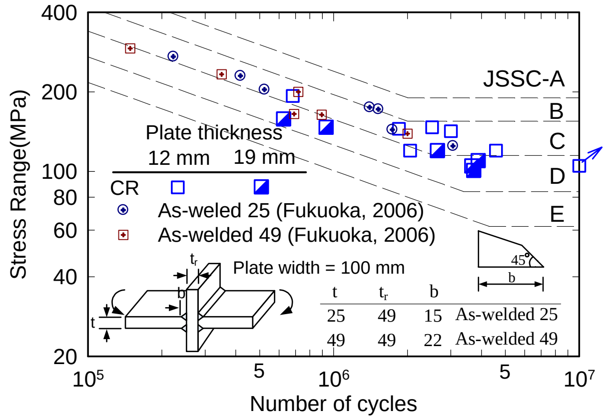
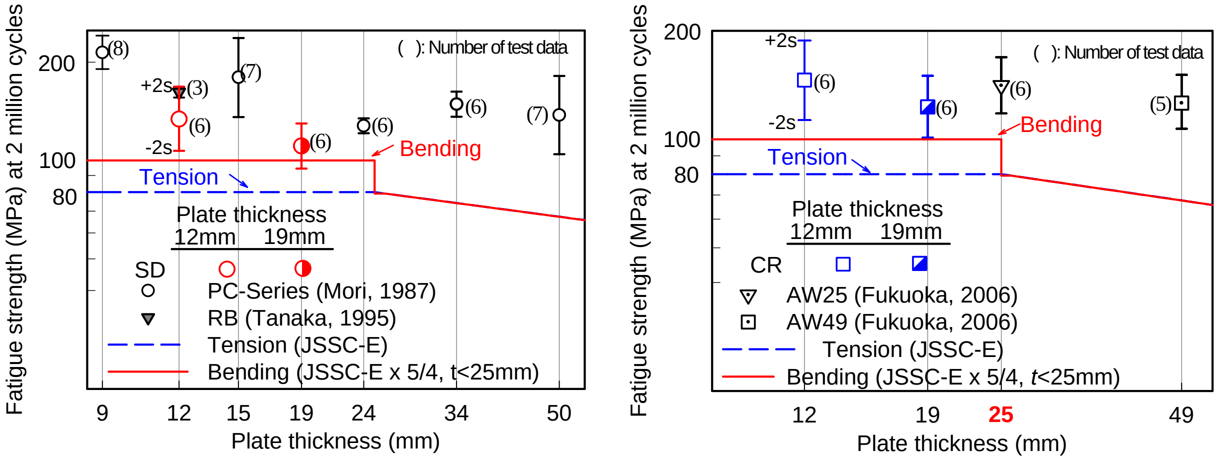


Fig.16 Fatigue test results of CR12, 19 in comparison with the previous test results

summarized here have 300 mm plate widths.

Shown in Fig.16 are the test results of CR19 and CR12 in comparison with the previous results of the cruciform joint with K-butt weld, which has two different plate thicknesses, 25 and 49 mm, tested by Fukuoka *et al.*[4]. As can be seen, the test results of CR12 and CR19 are almost equal to those of the as-welded specimens, regardless of their different dimensions.

The increase of plate thickness usually reduces the fatigue



(a) SD12, 19 and previous test results (b) CR12, 19 and previous test results

Fig.17 Variation of fatigue strength for bending due to plate thickness change

strength of welded joint. The JSSC specifies that, if plate thickness is 25 mm or more, the fatigue strength of welded joint be corrected by using the following equation.

$$C_t = \sqrt[4]{25/t} \quad (t \geq 25) \tag{3}$$

where t is a plate thickness in mm.

To investigate the fatigue strength variation due to plate thickness change in bending, the fatigue strength at 2 million cycles of each type of specimen is calculated and plotted in Fig.17. A dotted line stands for the design strength for tension and a solid line represents the design strength for bending, relating to the plate thickness change. As can be seen, the fatigue strengths at 2 million cycles of SD and CR specimens tend to decrease by the increase of plate thickness, relatively for other test results. In comparison with the previous test results, the fatigue strength at 2 million cycles of SD12 is about 17% lower than that of RB[11], in spite of the same plate thickness, 12 mm. The fatigue strength of SD19 is about 13% lower than that of 24 mm plate thickness specimen. The fatigue strength at 2 million cycles of CR19 is also around 12% lower than that of AW25[4]. The test results of all specimens exceed the design strength for bending.

The fatigue strength regarding a type of loading, tension and bending is shown in Fig.18. The test results of CR19 and CR12 are plotted with those of cruciform fillet welded joint specimens tested in tension[11),12]. As can be seen, the test results of CR12 and CR19 are higher than those of cruciform fillet welded joint specimens tested in tension.

4. FATIGUE STRENGTH EVALUATION BY ONE-MILLIMETER STRESS METHOD

4.1 Finite element model

To evaluate the fatigue strength of each type of welded joint by using one-millimeter stress method, finite element analysis (FEA) is required. Stress distribution in the expected crack path

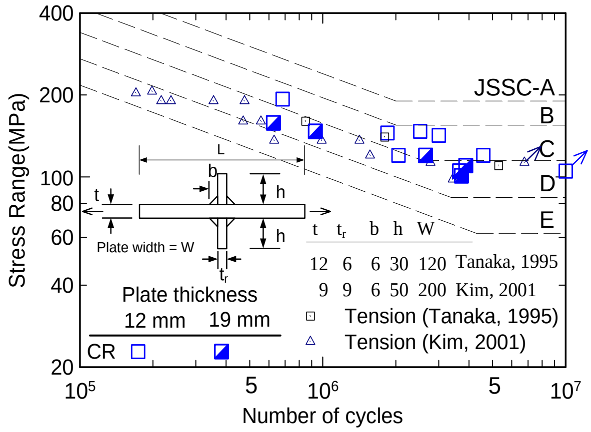
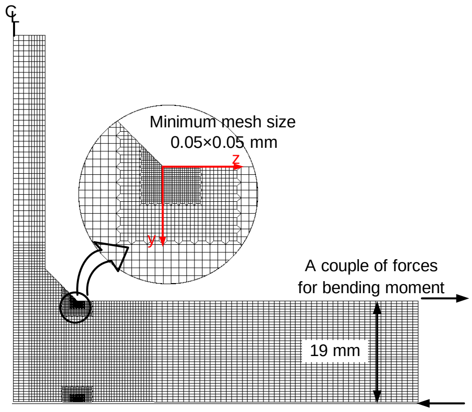


Fig.18 Fatigue test results of CR12, 19 in comparison with the previous test results for tension

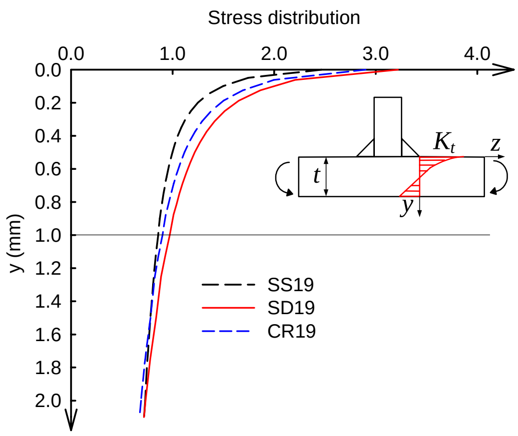
direction is usually determined by two or three dimensional finite element analysis. The entire analysis is carried out using the COSMOS/M 2.9[13]. A plane strain model with four-node two dimensional elements is used in mesh definition for each welded joint model in this study. An example of finite element model, SD19, is shown in Fig.19(a), with meshing around weld toe region. Minimum mesh size in the weld toe region is 0.05 mm. In the present analysis, Young's modulus, E=200GPa and Poisson's ratio, v=0.3 are assumed.

4.2 Fatigue life prediction by one-millimeter stress method

The stress distributions in the expected crack path direction are shown in Fig.19(b). The stress at 1 mm in depth is taken as an indicator of global geometry of welded joint and used as a measure of fatigue strength. Xiao and Yamada[6] proposed a method of quantifying geometric stress in the weld toe region due to the overall geometry of welded joint. The local stress in a welded detail due to weld profile is considered to be comparable to the whole stress of a non load-carrying cruciform joint consisted of the base plate and attachment, which are about 10 mm thick and fillet size is 6 mm, referred to as reference detail.



(a) Example of finite element model (SD19)



(b) Stress distributions in crack depth direction

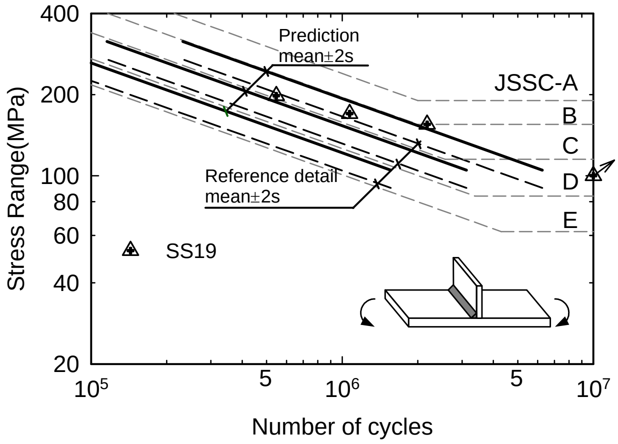
Fig.19 Finite element analysis

The geometric stress due to the overall joint geometry is evaluated 1 mm below the weld toe in the direction of the expected crack path. Stress concentration factor, K_t, at 1 mm in depth is 1.0 on the non load-carrying cruciform fillet welded joints subjected to tension. The scatter of test data of these cruciform joints as the reference detail, and then can be referred to determine fatigue strength of the objective welded detail.

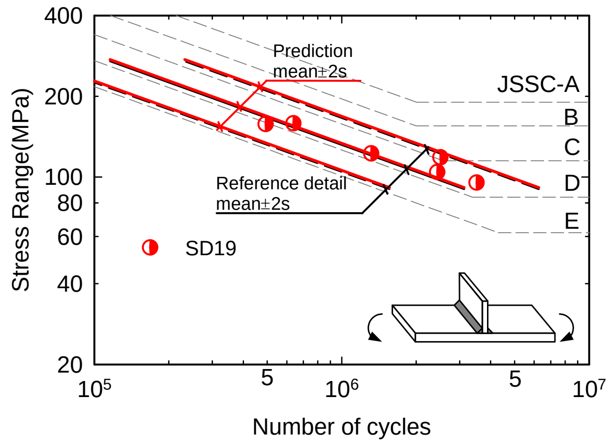
The one-millimeter stress method is employed to evaluate the fatigue strength of fillet welded joint subjected to bending. The stress at 1 mm in depth for each type of specimen is obtained from the stress distribution. The stresses at 1 mm depth are 0.858, 0.973 and 0.901 for SS19, SD19 and CR19, respectively. Using these stresses at 1 mm in depth and the regression S-N curves of the reference detail, fatigue strength evaluation is carried out on each type of specimen and the results are plotted with the fatigue test data in Fig.20.

As can be seen, the predicted life ranges of SD19 and CR19 are in agreement with the test data, while that of SS19 may be a little more conservative than its test data.

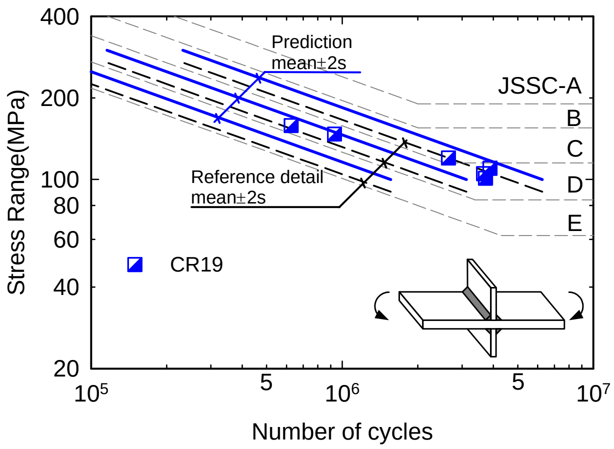
5. SUMMARY



(a) SS19



(b) SD19



(c) CR19

Fig.20 Fatigue life prediction by one-millimeter stress method

The focus of this study is to investigate the fatigue crack propagation behavior of fillet welded joints subjected to bending. The fatigue test has been carried out on three types of the fillet welded joints subjected to bending load and crack shape development has been demonstrated.

As in the case of the previous test results of specimens with 12 mm thick plate[5)], the test results in this study have presented that most fatigue cracks form relatively flat semi-ellipses during crack propagation and propagate to about 80% of plate thickness before failure. The values of aspect ratio, *a/c*, decrease at the early stage of crack propagation and then maintain lower until failure, because small and multiple cracks coalesce at an earlier time and form long and shallow semi-ellipses.

The fatigue strength at 2 million cycles of SS19 is 1.27 and 1.15 times higher than those of SD19 and CR19, respectively.

The fatigue strengths at 2 million cycles of SD and CR specimens are over 10% different from the previous test results[10),11)] in terms of the plate thickness increase.

The fatigue test results associated with a type of loading, tension and bending, show that bending contributes to the longer fatigue life than tension.

The predictions by using one-millimeter stress method are consistent with the test results of the welded joint subjected to bending.

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