

# Fatigue crack initiation and propagation life assessment of butt joint considering the effect of corrosion\*

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The purpose of present study is to develop a numerical technique for the fatigue life assessment considering the effect of corrosion. For assessing the fatigue crack initiation life, an elastoplastic constitutive model was developed. The model incorporates a novel cyclic plasticity theory together with a crack initiation criteria, which is extended to consider the surface changes. On the other hand, the crack propagation was taken into account based on linear fracture mechanics considering SIF ranges and an extension of the Paris' law to consider the corrosion effect. The numerical results showed a good agreement with the experimental data. Moreover, the model prediction was able to catch a reduction of the fatigue life due to the degradation of the mechanical properties in a corrosive environment.

**Key Words:** Fatigue, Corrosion, Welded Joint, Elastoplastic FEM, Fatigue Crack Initiation Life

## 1. Introduction

Fatigue failure is generally known as the most common failure mechanism in machine and structures<sup>1)</sup>. Fatigue life of welded joints is affected mainly by the weld geometry<sup>2)</sup> (toe radius and angular distortion, etc.) and by residual stresses. Many cases have been reported in which fatigue cracks occur from the welds and cause fatigue failure. Moreover, the effect of corrosion is superposed on fatigue performance depending on the environmental conditions<sup>3)</sup>.

The corrosion in the materials leads to the phenomenon called corrosion pitting<sup>3)</sup>. Usually, fatigue cracks initiate and propagate from corrosion pits since the presence of corrosion pits leads to local stress concentration<sup>4), 5)</sup>. It means that the surface condition is a significant factor that affects fatigue performance. On the other hand, a large number of experimental works<sup>3), 6), 9)</sup> have reported that fatigue life of welded joints in corrosion environment may or may not be deteriorated compared to that in air. The complexity of the results would be maybe due to the combined influences related to cyclic frequency in fatigue tests and the resultant change of geometries (toe radius, flank angle, crack tip, crack surface), residual stress and deformation, etc. Accordingly, the fatigue behavior of welded joints under corrosive environment is complex. It is difficult to carry out experiments due to limited time, the high costs and different conditions in the experimental campaigns. On the other hand, numerical analyses can reduce the time and costs, and allows us to conduct parametric studies in order to understand the main factors that affect the material performances. Therefore,

it is important to develop the evaluation methodology for fatigue problems considering the effects of the corrosion by numerical analyses.

The authors have recently developed a numerical model for the fatigue life assessment, fatigue crack initiation and propagation life assessment<sup>7)</sup>. The constitutive equations of the developed theory<sup>8)</sup> can describe the elastoplastic response of the material. The fatigue crack initiation life assessment is based on elastoplastic finite element analyses (FEA), whereas the fatigue crack propagation life assessment is based on linear fracture mechanics. This methodology has been developed to obtain a better characterization of the material behavior and to allow a better design of components or structures, enhancing the fatigue performances of metallic materials. Here, this method is expected to be developed to consider the corrosion effect on fatigue.

The purpose of the present study is to develop a numerical technique for fatigue life (fatigue crack initiation and propagation life) assessment considering the corrosion effects.

## 2. Fatigue crack initiation life assessment

The target of this study is to reproduce numerically the results

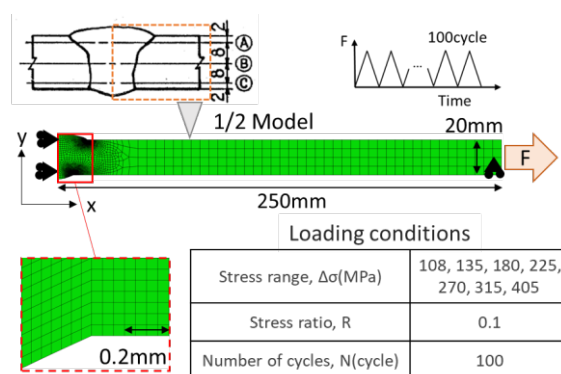


Fig. 1 FE model of the butt joint geometry and boundary conditions simulating the fatigue test

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of fatigue tests on butt joints in air and artificial seawater conducted by Yajima et al<sup>9)</sup>. Fig. 1 shows the FE model that reproduces the geometry of the welded joint and the boundary conditions used in the fatigue tests. A mesh refinement was performed at the weld toe, where the stress concentration is expected, adopting a minimum element size of 0.05mm. The toe radius influence and the presence of angular distortions are not considered in this study. The cyclic plasticity model, named fatigue SS model<sup>8)</sup>, was used as a constitutive model for the material and it was implemented via user subroutine for the commercial code ABAQUS (Ver6.14-5). The fatigue SS model<sup>8)</sup> is derived from the unconventional elastoplasticity model<sup>10)</sup> to enrich the cyclic plasticity behavior with an isotropic scalar damage variable for the description of the cyclic hardening and softening behavior. A cyclic loading condition, up to 100 cycles, was applied on the right end of the model (i.e. stress ratio of R=0.1) in order to simulate the experimental set up (see Fig. 1).

Fig. 2 shows the distribution of cumulative plastic strain after 20 cycles. The higher accumulation of irreversible deformation is located near the lower toe. Fig. 3 shows the stress-strain response (loading axis direction) at the element that exhibits the maximum

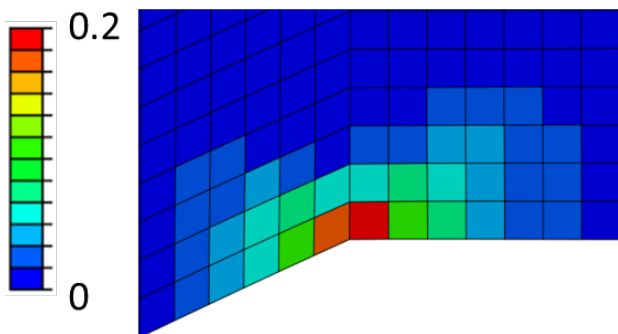


Fig. 2 Distribution of cumulative plastic strain after 20 cycles ( $\Delta\sigma=315\text{MPa}$ )

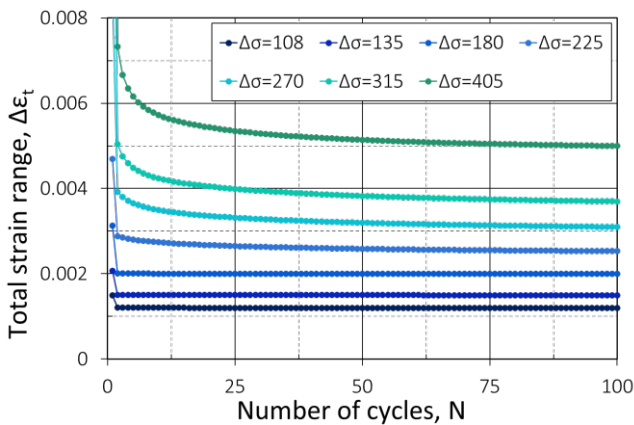


Fig. 4 Relationship between total strain range  $\Delta\epsilon_t$  and number of cycles  $N$

cumulative plastic strain. Fig. 4 shows the total strain range, defined as the differences between the maximum and minimum strains at each cycle. The fatigue crack initiation life was assessed using the proposed Eq. 1.

$$\frac{\Delta\epsilon_t}{2} = (1 - \alpha)0.415N_C^{-0.606} + (1 - \beta)0.00412N_C^{-0.115} \quad (1)$$

where  $N_C$  is the crack initiation life,  $\Delta\epsilon_t$  is the total strain range and the  $\alpha$  and  $\beta$  are parameters that take into account the corrosion initiation and progression. It should be mentioned that Eq. 1 has been modified by the authors to consider the corrosion effect by the parameters  $\alpha$  and  $\beta$ . Eq. 1 was originally formulated based on an experimental database in air<sup>1)</sup>, which corresponds to the Eq.1 when  $\alpha$  and  $\beta$  are both null. In detail, the parameter  $\alpha$  is representative of the hydrogen effect on the reduction of ductility, and the parameter  $\beta$  is representative of the corrosion effect in terms of surface changes, for example, surface roughness decreases the fatigue limit<sup>1)</sup>. In this study,  $\alpha$  is set to 0, and  $\beta$  is changed from 0.1 to 0.2, and to 0.3, which means that the corrosion effect is more severe for higher values of the parameter. The response of Eq. 1 is shown in Fig. 5.

As it can be seen in Fig. 4, the total strain ranges, for each loading

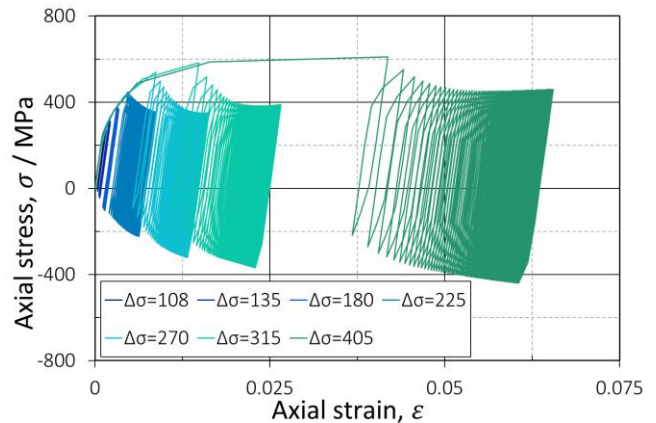


Fig. 3 Stress-strain relationship in the element with maximum cumulative plastic strain

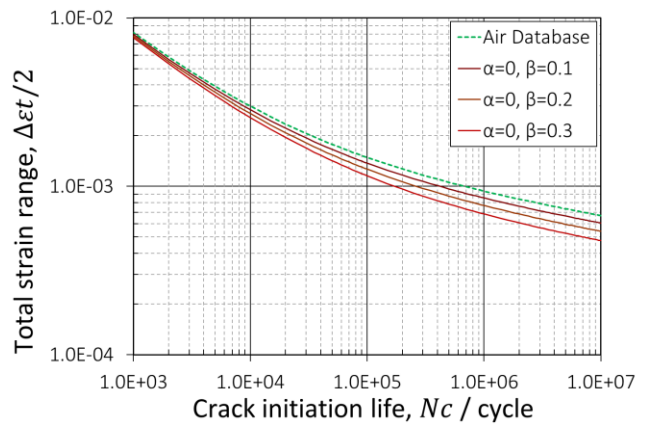


Fig. 5  $\Delta\epsilon_t/2 - N_C$  relationship (Dashed line: experimental database, Red line: proposed equation)

conditions, seem to be saturated at the 100th cycle. Therefore, the values of  $\Delta\varepsilon_t$  at the 100th cycle were adopted for the evaluation of the crack initiation life by means of Eq. 1. S-N relationship of fatigue crack initiation life is shown in Fig. 6. It can be seen that fatigue crack initiation life considering the corrosion effect (●, ▲, ■) is deteriorated by increasing  $\beta$  compared against the solution with  $\beta=0$  (i.e. the result in air (○)).

### 3. Fatigue crack propagation life assessment

The fatigue crack propagation life is based on fracture mechanics. The initial crack is located where crack initiation was predicted by the elastoplastic numerical simulation in the previous section. The initial crack length is set to be 0.05mm. Fatigue crack propagation life is evaluated by using the relationship between crack length  $a$  and stress intensity factor  $\Delta K_{eq}$ , based on elastic FE analyses and on the extended Paris' law  $da/dN = C(\Delta K)^m$  with Eq. 2, adopted to fit the experimental result.

$$C = C_{air} \left[ b + (d_2 - b) \left\{ 1 + \left( \frac{K_{cri}}{\Delta K} \right)^{d_1} \right\}^{-1} \right] \quad (2)$$

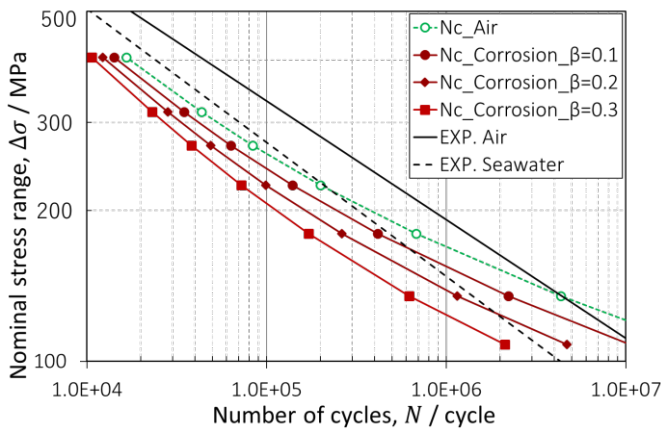


Fig. 6 Relationship between the stress range and the fatigue crack initiation life

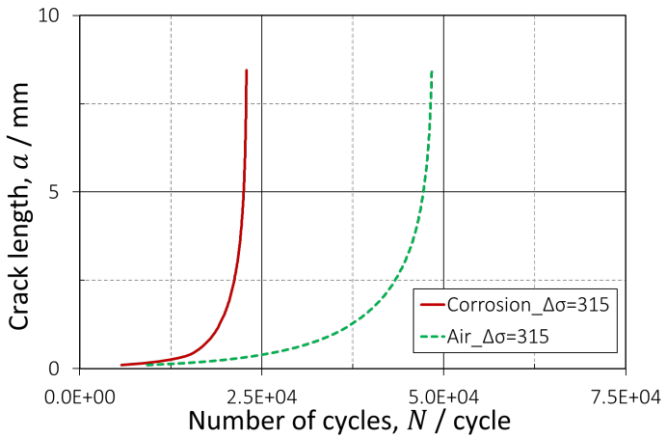


Fig. 8 Relationship between the crack length and the number of cycles ( $\Delta\sigma=315\text{MPa}$ )

where  $C_{air}$  is a material constant obtained by interpolation of the experimental results<sup>11)</sup> in air.  $\Delta K$  is the stress intensity factor (SIF) range at the crack tip.  $b$ ,  $d_1$ ,  $d_2$ , and  $K_{cri}$  are material constants that contribute to the acceleration of fatigue crack growth rate. Fig. 7 shows the fatigue crack propagation characteristic of the base metal of the butt joint<sup>11)</sup>. The experimental result shows that the fatigue crack growth rate under the corrosive environment (●) is accelerated compared to that in air (○ and dashed line). Therefore, in this study, the material constant  $C$  in the Paris' law  $da/dN = C(\Delta K)^m$ , was extended to be a function of the SIF range,  $\Delta K$ .

Table 1 shows the values of the parameters adopted in Eq. 2. The

Table 1 Parameters used for the extended Paris' law

Parameter	Value
$C_{air}$	1.28E-12
$b$	1.6
$d_1, d_2$	60, 3.0
$K_{cri}$	19

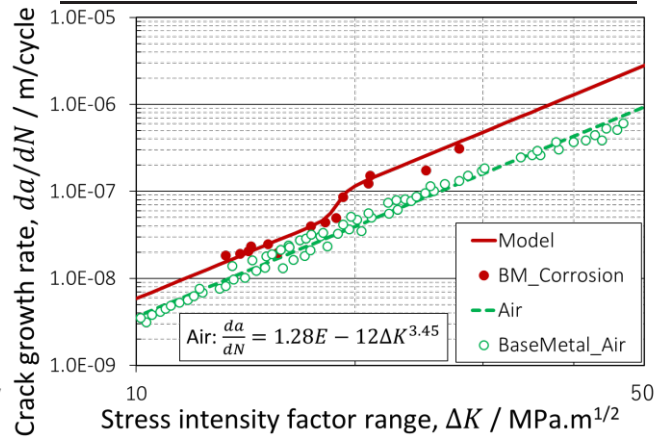


Fig. 7  $da/dN - \Delta K$  relationship (Solid line: extended Paris' law with Eq.2, others: experimental results)

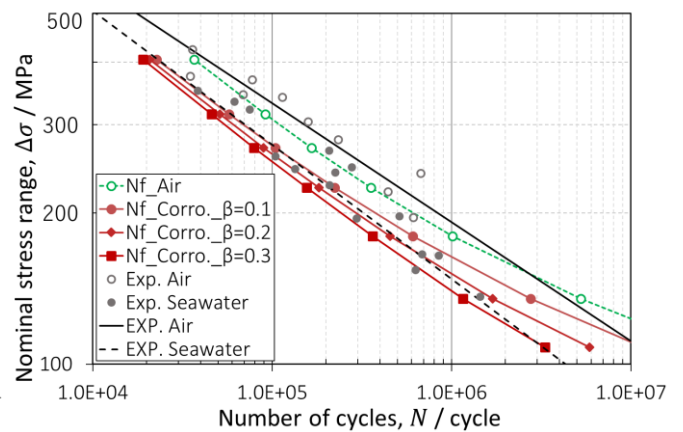


Fig. 9 Results of the fatigue life assessment (Fatigue crack initiation life and propagation life)

extended Paris' law relationship using Eq. 2 is shown as a solid line in Fig. 7.  $b$  and  $d_2$  are representative of how many times the growth rate in a corrosive environment is accelerated compared with the growth rate in air.  $K_{cri}$  represents the transition point of the acceleration. The proposed Paris' law can predict the acceleration. The reason for the transition behavior of the crack propagation rate was reported as the results of the hydrogen embrittlement at the crack tip<sup>12)</sup>. Fig. 8 shows the relationship between crack length  $a$  and number of cycles  $N$ . The solid and dashed line are the results considering and not considering the corrosion effect, respectively. It can be seen that fatigue crack propagation life considering the corrosion effect is deteriorated by the corrosion effect on the acceleration.

#### 4. Results and discussion

Fatigue life is defined as the sum of fatigue crack initiation life and propagation life. The S-N relationship of fatigue life is shown in Fig. 9. The results of the analyses considering or not the corrosion effect are shown as marks with (●, ▲, ■) and (○), respectively. The solid and dashed lines are the experimental results obtained in air and artificial seawater<sup>9)</sup>, respectively. Fig. 9 indicates that numerical analyses with and without the corrosion effect are in good agreement with the experimental results (especially  $\beta = 0.3$  when considering the corrosion effect). This indicates that this assessment method is able to evaluate fatigue life under a corrosive environment.

#### 5. Conclusion

In this study, the numerical technique for fatigue life assessment considering the corrosion effects was proposed. Fatigue life of butt joints was assessed by two separate approaches, fatigue crack initiation and propagation life assessment. The fatigue crack initiation life has been evaluated based on elastoplastic analyses and the proposed Eq. 1. The fatigue crack propagation life has been assessed considering a linear fracture mechanics approach with the extended Paris' law in Eq. 2. The results of fatigue life assessment are in good agreement with the experimental results both in air and seawater, indicating that it is possible to reproduce the fatigue life

reduction due to corrosion effects.

The relationship among the parameters ( $\alpha$  and  $\beta$ ) related to the corrosion phenomenon (e.g. surface roughness, frequency, or chemical reaction, etc.) needs to be further studied. Moreover, considerations on the change in shape (i.e. thickness reduction) in FEA, or implementation of 3D analyses, should also be investigated.

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