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Technical Report

Fatigue Life Prediction of Welded Structures Based on Crack Growth Analysis

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Abstract

A fatigue life prediction system for welded structures has been developed based on crack growth analysis. In the developed system, the fatigue life can be predicted taking into account the effects of the residual stress and the load sequences by the crack opening and closure simulation. Furthermore, the effect of fatigue strength improvement techniques, such as UIT, can be accurately predicted by the developed system.

1. Introduction

With the latest tightening of energy supply conditions, the social pressures for development of ships, bridges, construction machines, and other welded structures with longer service lives and lower life cycle costs (LCC) is increasing. The thickness of the steel plates for these structures and their structural details are defined largely based on the fatigue design of the weld joints. In order to be able to design and rationalize limited maintenance materials for wider application, it is therefore essential to enhance the accuracy of fatigue life prediction. Post-weld treatment methods, such as grinding, tungsten inert gas (TIG) dressing, hammer peening, ultrasonic impact treatment (UIT),[1, 2] etc., are applied to weld toes as measures against the fatigue of weld joints, but no means have thus far been established to adequately evaluate the effects of these treatment methods.

To improve the reliability of welded structures, Nippon Steel Corporation has undertaken to set up a framework of overall solutions to problems of fatigue fracture,[3] and as part of such activities, has developed a system of fatigue life prediction with high accuracy.[4, 5] This fatigue life prediction method, which employs crack growth analysis based on fracture mechanics, consists of the following procedures: i) small initial cracks are assumed to form first at the surface of a weld toe, where fatigue cracks are likely to occur; ii) stress intensity factors are calculated for the deepest and surface points of the surface cracks; iii) an effective range of the stress intensity factor is defined using a crack opening/closing model; and iv) the propagation behavior of the fatigue cracks is simulated by applying the fatigue crack growth law. The crack opening/closing model is a means for simulating crack opening and closing behavior, wherein the residual plastic region of the crack wake is discretely expressed using bar elements by applying a strip yield model.[6, 7] This approach makes it possible to accurately take into consideration the influence of the residual stress and loading sequence on the propagation behavior of the fatigue cracks. Herein are presented the outline of the developed fatigue life prediction method and examples of its application to welded joints.

2. Outline of Fatigue Life Prediction Method

2.1 Simulation of propagation and coalescence of surface cracks

Fig. 1 schematically shows the common propagation behavior of fatigue cracks that occur at a welded joint. Fatigue cracks usually originate in a plurality along a weld toe where the stress concentra-

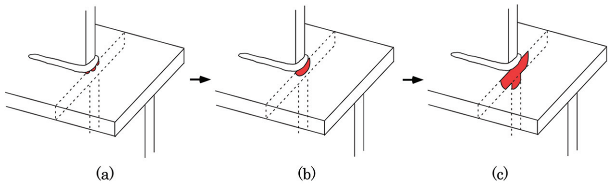

Fig. 1 Behavior of fatigue cracks in a welded structure
(a) Initiation of cracks, (b) Propagation and coalescence of surface cracks, (c) Propagation of a through-the-thickness crack

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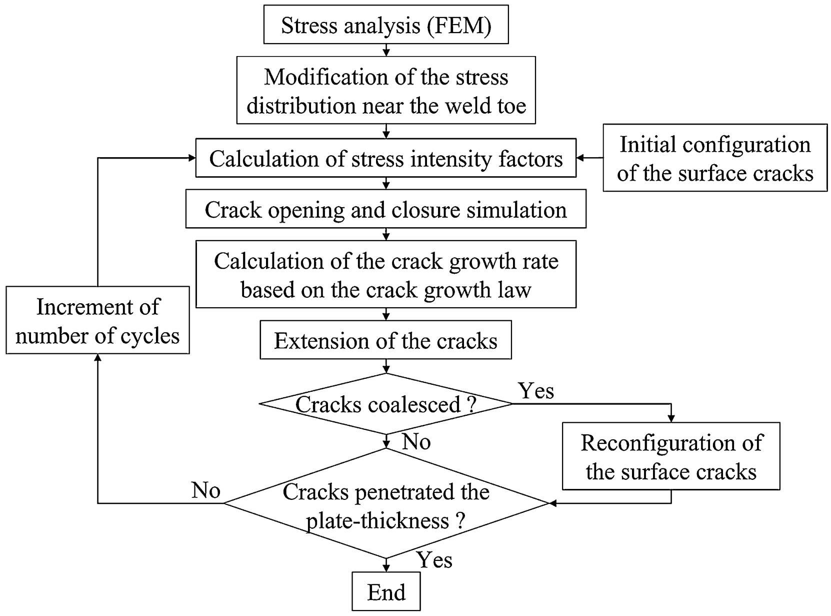

Fig. 2 Procedure of the fatigue crack propagation analysis

tion is significant, and as they propagate, coalesce to form a single surface crack. The coalesced crack continues to grow to the other side of the plate and then further, resulting in a final failure of the joint. In this fatigue life prediction method, some minute surface cracks are assumed to nucleate at the weld toe, their growth and coalescence are simulated, and the time period until the crack develops across the plate thickness, or the fatigue life of the welded joint, is calculated. The simulation procedures are as follows (see also **Fig. 2**):

(1) The distributions of the stress and residual stress in the sectional plane along which the fatigue cracks are assumed to propagate are obtained based on FEM analysis of a welded joint using three-dimensional solid elements.

(2) The stress concentration coefficient K_t for the welded joint in question is calculated using the estimation formula proposed by Tsuji [8] and based on the weld toe radius ρ and other local dimension parameters of the joint. In addition, the stress distribution near the weld toe is obtained from the calculated value of K_t and using Glinka's formula to express the stress distribution near a weld toe.[9] The stress distribution thus obtained is then connected smoothly to that obtained according to Item (1) above.

(3) The stress intensity factors for the deepest and the surface points of the cracks that are assumed to form at the weld toe are calculated from the distributions of the stress and residual stress obtained in Items (1) and (2) above using the weight function method.[10]

(4) Via a crack opening/closing simulation[4] that applies a strip yield model, the effective range of the stress intensity factor ΔK_{eff} (the range of the stress intensity factor corresponding to the load range in which the crack in question is open) with respect to the deepest and the surface points of the cracks is calculated. The method used for the crack opening/closing simulation will be outlined in the following sub-section.

(5) According to the fatigue crack growth law with respect to ΔK_{eff}, the crack growth Δa per prescribed number of loading cycles ΔN is calculated with respect to the deepest and the surface points of each of the cracks, and the cracks are extended accordingly.

(6) The coalescence or otherwise of adjacent cracks is judged. If any two cracks are deemed to have coalesced into one, the unified crack is redefined. The coalescence judgment and the redefinition of the unified crack are achieved according to WES 2805-07.[11]

(7) When the depth of a crack is regarded to have become equal to the plate thickness, the analysis is terminated, and the number of loading cycles up to that point is defined as the fatigue fracture life N_f of the joint. When the depth of the crack is less than the plate thickness, ΔN is added to the number of loading cycles, and the analysis operation returns to Item (3) above.

2.2 Crack opening/closing simulation

It is known that, as a result of the propagation of a fatigue crack in the tensile plastic zone generated at the crack tip, residual plasticity zones form on the crack surfaces, which leads to crack closure before the minimum load is reached. In addition, the propagation rate of fatigue cracks in steel materials is influenced significantly by the stress ratio, the residual stress, and the load history, which are closely related to the crack opening/closing behavior. Therefore, to accurately estimate the fatigue life of a welded joint, it is important to analyze the opening/closing behavior of fatigue cracks.

It has been known that, when a crack is closed, the state of its being closed does not influence the stress singularity near the crack tip. Thus, the load on a fatigue crack contributes to its growth only when the load is in the range where the crack is open (see **Fig. 3**), and the following fatigue crack growth law holds true:

$$da / dN = C \left\{ \Delta K_{\text{eff}}^{m} - \left(\Delta K_{\text{eff,th}} \right)^{m} \right\} \qquad (1)$$

where da/dN is the fatigue crack growth rate, ΔK_{eff} is the effective range of the stress intensity factor (the range of the stress intensity factor corresponding to the load range in which the crack is open),

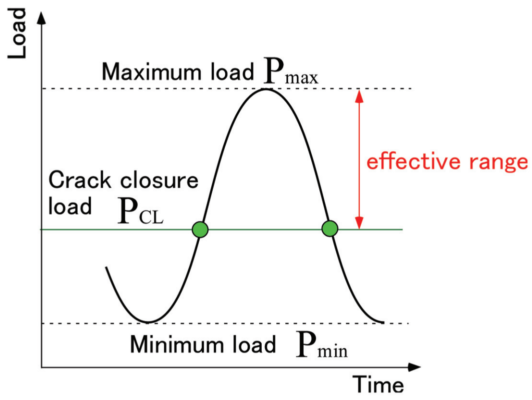

Fig. 3 Definition of effective load range

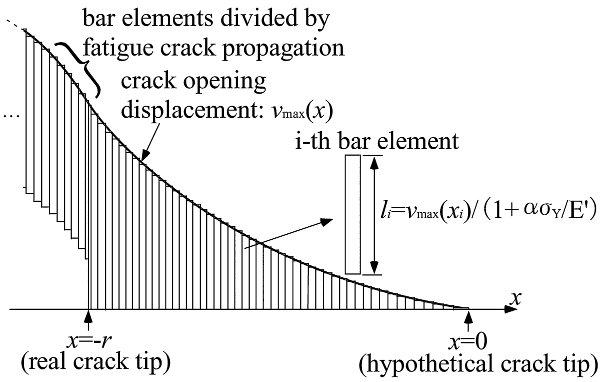

Fig. 4 Configuration of bar elements based on the crack opening displacement

and C, m, and $\Delta K_{eff,\,th}$ are material constants.

Here, the effective range of the stress intensity factor ΔK_{eff} can be estimated based on a crack opening/closing simulation.[4] In addition, from the basic concept of the strip yield model, the crack opening displacement under the maximum load $v_{max}(x)$ can be obtained by the following equation:

$$v_{max}(x) = \frac{2\sqrt{2(-x)}\hat{K}_{max}}{E'\sqrt{\pi}} - \frac{2\alpha\sigma_Y}{\pi E'}\int_0^r 1n\left|\frac{\sqrt{\xi}+\sqrt{-x}}{\sqrt{\xi}-\sqrt{-x}}\right| d\xi \qquad (2)$$

$$E' = \begin{cases} E & \textit{for plane stress} \\ E/(1-\nu^2) & \textit{for plane strain} \end{cases}$$

where $\hat{K}_{max}$ is the stress intensity factor for the tip of a virtual crack under the maximum load, σ_Y is the yield stress, α is the tensile plastic constraint factor, r is the size of the tensile plastic zone, E is Young's modulus, ν is the Poisson ratio, and ξ is the distance from the crack tip to the concentrated force couple. Here, $-r < x < 0$ corresponds to a virtual crack zone and $x < -r$ to a real crack zone; when $-r < x < 0$, $v_{max}(x)$ represents the virtual crack opening displacement by plastic deformation, and when $x < -r$, $v_{max}(x)$ represents the real crack opening displacement.

Based on the value of $v_{max}(x)$, the bar elements of elastic-perfectly plastic solids are arranged in the virtual crack zone, as shown in **Fig. 4**. The bar elements in the virtual crack zone are assumed to be divided into upper and lower parts as the crack grows, and the divided parts are left on the crack surfaces as residual plastic regions. This assumption makes it possible to analyze the crack opening and closing behavior in each loading cycle, and to calculate the value of ΔK_{eff} in consideration of the effects of the stress ratio, the residual stress, and the load history.

3. Fatigue Life Prediction of Welded Joint under Variable Amplitude Loading

3.1 Stress and residual stress analyses

The analysis of an out-of-plane gusset welded joint was carried out as an example. First, an FEM model of the specimen was formulated using three-dimensional solid elements, and the stress distribution in the specimen under a unit tensile stress was calculated using elastic analysis. **Fig. 5** shows the specimen joint, and **Fig. 6** depicts a mesh model of the portion of the joint near a weld toe that was used for the FEM analysis. Young's modulus was assumed to be 206 GPa, and the Poisson ratio to be 0.3. The stress distribution in the plate thickness plane including the weld toe was extracted from the analysis results, and the stress concentration coefficient K_t was calculated according to the procedure described in Item (2) of Sub-section 2.1 above. The stress distribution near the weld toe was then modified accordingly. On the assumption that the weld toe radius was 1 mm and the flank angle was 32.4°, the stress concentration coefficient K_t was calculated to be 3.04.

The distribution of the residual stress was estimated using the thermo-elastic-plasticity FEM, where the material properties of the base metal and the weld metal were assumed to be the same. The yield stress at room temperature (20°C) was set at 350 MPa, Young's modulus at 206 GPa, and the Poisson ratio at 0.3. Assuming that the

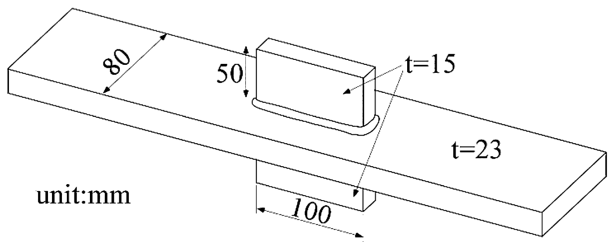

Fig. 5 Out-of-plane welded gusset joint

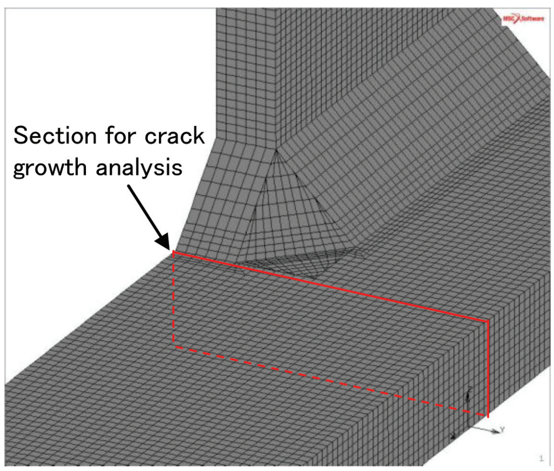

Fig. 6 Finite element model

stress-strain curve was of the bi-linear type, the work hardening coefficient was set at 1/100 of Young's modulus. In addition, in consideration of the reference literature,[12] the yield stress, Young's modulus, the work hardening coefficient, the thermal conductivity, the specific heat, and the coefficient of linear expansion were assumed to change as a function of the temperature. A welding heat input of 900 J/mm was applied to the entire bead simultaneously, and then the joint was cooled naturally through the surface in the atmosphere at 20°C for 3,600 s. In the same manner as in the stress analysis, the residual stress distribution in the section shown in Fig. 4 was extracted from the analysis results and used for the fatigue crack growth analysis. The MSC. Marc 2005r2 solver was used for the analysis of the stress and residual stress.

3.2 Conditions for fatigue crack growth analysis

A single initial crack was assumed to form at the toe of the gusset weld on the centerline of the specimen. Based on the recommended size of an initial crack for analysis of fatigue crack propagation from a welded joint according to the International Institute of Welding (IIW),[13] the initial crack was assumed to be semicircular and 0.15 mm in depth. In addition, based on the da/dN- ΔK mean design curve[14] of the Japanese Society of Steel Construction (JSSC), the fatigue crack propagation constants were set as follows: $C = 1.5 \times 10^{-11}$, $m = 2.75$, and $\Delta K_{eff,\,th} = 2.9$ [MPam$^{1/2}$]; the values for these constants given in WES 2805-07 [11] and other literature reports are substantially the same. The tensile plastic constraint factor α was set at 2.5 for the deepest point of the crack and 1.3 for the surface points of the crack, because the deepest point is assumed to be in the plane strain state and the surface points in the plane stress state. These values were obtained through elasto-plastic FEM analysis.

3.3 Comparison of calculated and experimental results

The analysis of fatigue crack propagation and the fatigue tests were conducted under the following two loading conditions.

LC1: Constant-amplitude loading in the stress range of 100 MPa and at a stress ratio of 0.1

(a beach mark after every 100,000 cycles), and

LC2: In addition to the loading of LC1, an overload of 200 MPa was applied after every 200,000 cycles.

Note that the specimen joints for the fatigue test were prepared by CO_2 fillet welding with a leg length of roughly 10 mm using SM490B base metal plates according to JIS G 3106 and YGW11 solid welding wire according to JIS Z 3312.

In **Fig. 7**, the fatigue crack growth curves obtained through the simulation and for the actual tests are compared. Here, the abscissa represents the number of loading cycles to failure, and the ordinate the crack depth, which was counted for the tests based on the beach marks on the crack surface. The tests revealed that the fatigue life under LC2 was nearly twice that under LC1. This difference is due to the delay of fatigue crack propagation when the overload was imposed during LC2. The simulation results agreed well with the test results, which indicates that the developed model is good for predicting the fatigue life of welded joints when accurately taking into account the effects of overloads .

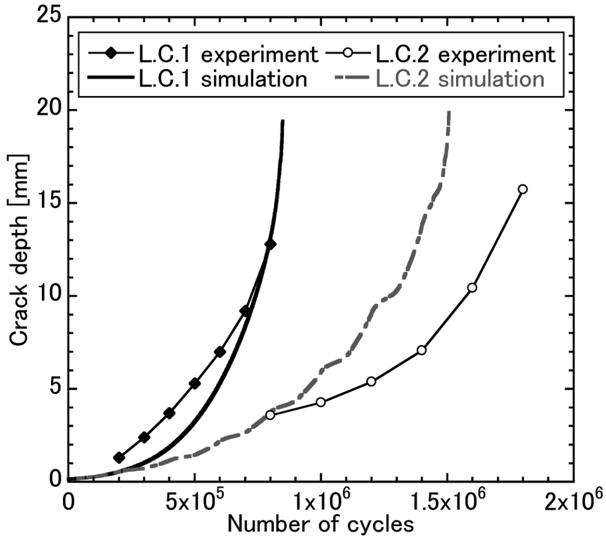

Fig. 7 Fatigue crack growth curves

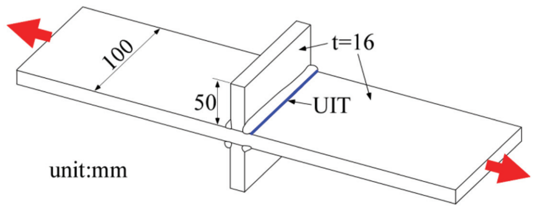

Fig. 8 Cruciform welded joint

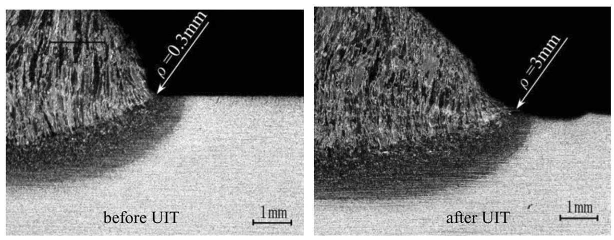

Fig. 9 Geometry of the welded-toe

4. Analysis of Effects of UIT on Improving the Fatigue Strength

4.1 Specimens

The dimensions of the specimen joints used for this study are shown in **Fig. 8**. The non-load-carrying cruciform joints were welded using CO_2 fillet welding with SM490B base metal plates according to JIS G 3106 and YFW-C50DR flux-cored welding wire according to JIS Z 3313.

Some specimens underwent UIT along the toes of the weld beads on the main plate. The treatment was conducted using an Esonic™ 27 UIS made by Applied Ultrasonic and pins designed exclusively for UIT use (3 mm tip radius and 3 mm diameter) under the following conditions: frequency, 27 kHz; power output, roughly 1 kW; shifting speed, roughly 100 mm/min. The sectional shapes of a weld bead before and after the treatment can be seen in **Fig. 9**. While the weld toe radius ρ was roughly 0.3 mm before the treatment, it increased to roughly 3 mm after the treatment, because the pin tip radius was transcribed to the weld toe.

4.2 Estimation of stress distribution

As described in Sub-section 3.1, the elastic stress distribution of the specimens was estimated by FEM analysis using three-dimensional solid elements while applying a unit tensile stress to the speci-

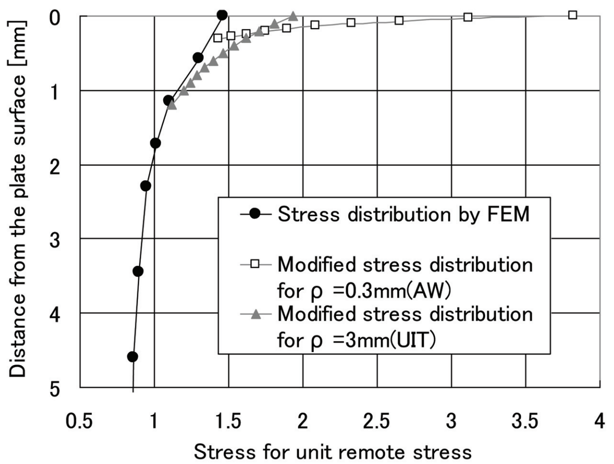

Fig. 10 Stress distribution near the weld-toe

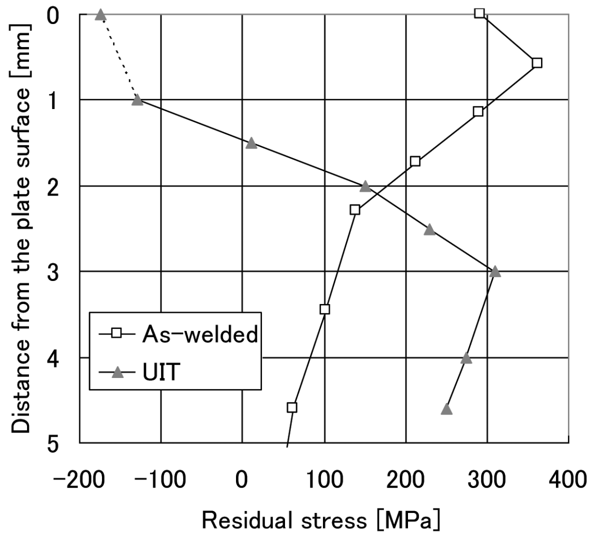

Fig. 11 Residual stress distribution near the weld-toe

men. The stress distribution in the plate section at the weld toe was then extracted from the analysis results, and the stress distribution near the toe was modified in consideration of the local weld geometry. In the calculation of the stress concentration coefficient K_t, the weld toe radius before and after UIT was set at 0.3 mm and 3 mm, respectively, and the flank angle was set at 45° both before and after UIT. As a result, K_t = 4.02 and 2.03 before and after UIT, respectively. **Fig. 10** shows the stress distribution near the weld toe in the width center portion of the specimen with and without the stress distribution modification.

4.3 Estimation of residual stress distribution

The distribution of the residual stress before UIT was estimated using the thermo-elastic-plasticity FEM as in Sub-section 3.1. To determine the residual stress after UIT, on the other hand, neutron diffraction analysis was employed [15, 16] using instrumentation at the Tokai Research and Development Center of the Japan Atomic Energy Agency. T-joints composed of a 29 mm-thick by 50 mm-wide flange and a 12 mm-thick by 50 mm-wide web, both hade of SM490B, were welded, subjected to UIT, and used as the specimens for the residual stress measurements. Although the joint shape was different from that of the fatigue test specimens, it was assumed that there was no substantial difference in the residual stress near the welded joint, because the joints had the same material strength and were subjected to the same UIT procedure. The measurements were taken in a sectional plane in the width center of the specimen to a depth of 5 mm from the UIT surface at 1 mm intervals in the depth direction. Note that the residual stress at the surface was not measured, and was assumed to be −175 MPa, or half of the yield stress of the base metal.

Fig. 11 shows the FEM analysis results for the residual stress distribution near the weld toe at the width center of the specimens with and without UIT. While a high tensile residual stress comparable to the yield strength was detected near the surface of the as-welded specimen (without UIT), the residual stress at 1 mm from the surface of the specimen after UIT was a compressive stress of roughly −130 MPa, and it was confirmed to gradually shift to the tensile region with increasing depth.

4.4 Comparison of calculated and experimental results

Fig. 12 shows the S-N curves (stress versus number of loading cycles to failure) obtained with the model and based on the test results. In both the analysis and the test, the stress ratio was set at 0.1 for the specimens without UIT, and at 0.1 and 0.5 for those after UIT. Note that, for the fatigue crack propagation analysis, five initial cracks were assumed to form at equal intervals along the weld toe. All of the other conditions were the same as those in Sub-section 3.2. In the analysis, the number of loading cycles along the abscissa represents the cycle at which the tip of a virtual crack reached the opposite side, or that for which crack propagation made the ligament section area so small that full-section yielding was deemed to have occurred under the maximum load. For the experimental results, the number of loading cycles along the abscissa represents that cycle at which the specimen actually broke.

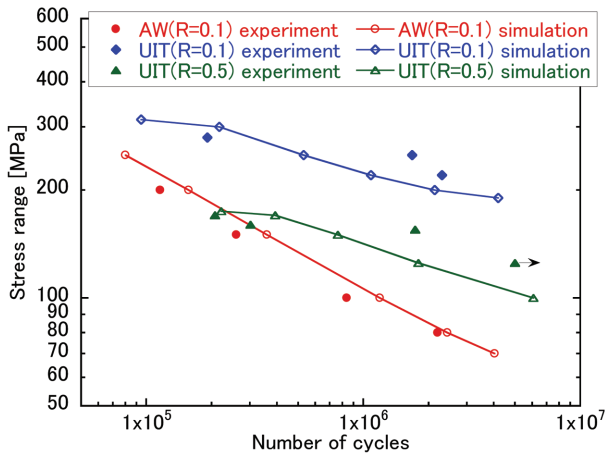

Fig. 12 Simulated and experimental S-N curves

As can be seen in Fig. 12, the analysis results agreed well with the test results. Under a stress ratio of 0.1, the fatigue strength of the specimens to which the UIT was applied was more than twice that of those without the UIT. Under a stress ratio of 0.5, on the other hand, the fatigue strength improvement effect of the UIT tended to be lower than that under a stress ratio of 0.1. These results indicate that the developed fatigue life prediction system is capable of quantitatively estimating the effects of UIT on the fatigue strength of cruciform welded joints when taking the influence of the stress ratio into consideration.

5. Conclusions

A fatigue life prediction system for welded structures has been developed, wherein small initial cracks are assumed to form along the toe of a weld bead, and their growth and coalescence behavior is simulated up to the time when a crack breaks through the plate thickness, which represents the fatigue life. The simulation of crack opening/closing behavior by applying a strip yield model makes it possible to adequately analyze the propagation of fatigue cracks considering the effects of the residual stress and loading sequence. The developed system proved capable of analyzing the effects of overloads on the fatigue life of welded joints and the fatigue strength improvement effects of UIT, and the prediction results agreed well with those obtained with actual fatigue tests. The system is expected to find wide application in the fields of fatigue design and maintenance for ships, bridges, plants, construction machinery, and other welded structures as a means for improving their reliability, extending their service life, and reducing environmental loads.

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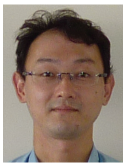
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