THE FATIGUE LIFE ESTIMATION METHOD FROM THE STRESS CONCENTRATION REGION WITH ZERO DEFECT :AN APPLICATION TO THE FATIGUE CRACK GROWTH SIMULATION CODE “FLARP” FOR THE IN-PLANE GUSSET WELDED JOINT

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THE FATIGUE LIFE ESTIMATION METHOD FROM THE STRESS CONCENTRATION REGION WITH ZERO DEFECT – AN APPLICATION TO THE FATIGUE CRACK GROWTH SIMULATION CODE "FLARP" FOR THE IN-PLANE GUSSET WELDED JOINT –

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ABSTRACT

In-plane gusset welded joints are very popular and used in many steel constructed structures.

Fatigue life estimations for this type of joint have been performed by applying the fatigue crack growth simulation code "FLARP" developed by the authors.

The fatigue crack shows the typical opening / closing behavior during fatigue crack growth. The plastic deformed layer in the crack wake, which represents the loading history indirectly, contributes to the behavior. The consideration of crack closure is essential in the estimation of the fatigue life. FLARP enables the quantitative simulation of the fatigue crack opening / closing.

By considering the cyclic plastic behavior ahead of a fatigue crack tip, the improved effective stress intensity factor range (ΔK_{RPG}) to denote the fatigue crack propagation law, which is formulated by replacing the crack opening load with the Re-tensile Plastic zone Generating load (RPG load), was defined. ΔK_{RPG} is adopted as the parameter for the fatigue life estimation by FLARP.

The validity of the fatigue life estimation by FLARP is confirmed by comparing the estimated S-N curves with the experimental results for the in-plane gusset welded joints.

INTRODUCTION

Although the applicaiton of TMCP steels reduces the number of brittle fracture accidents of welded built-up steel structures because of its high fracture toughness and good weldabilty, fatigue failure of structures has been increasing. This is considered to be due to the application of higher allowable stress to structures in the design stages due to the higher strength under static loading conditions.

Despite the many available fatigue life estimation methods, fatigue accidents still occur welded built-up structures. Most of proposed methods peripheralize the role of the cyclic plasticity around a crack tip. Consideration of the effect of the cyclic plasticity is imperative to the estimation of the fatigue crack growth for the following reasons:

1. The driving force for fatigue crack is supplied by the alternating cyclic plastic work generated ahead of a crack tip.
2. The fatigue crack propagates in the plastic zone generated ahead of a crack tip

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3. The plastic region is taken over the crack surfaces as the crack wake zone and the wake zone has an important contribution to the fatigue crack opening / closing, which dominates the fatigue crack growth.

An improved effective stress intensity factor range (ΔK_{RPG}) for use in the fatigue crack propagation law has been defined [1]. ΔK_{RPG} is formulated by replacing the crack opening load with the Re-tensile Plastic zone Generating load (RPG load) which was derived by considering the cyclic plastic behavior ahead of a fatigue crack tip.

The fatigue crack growth simulation code FLARP, which enables the simulation of the fatigue crack opening / closing, has been developed [2], [3]. The main characteristics of FLARP are as follows:

1. ΔK_{RPG} is adopted as the parameter for the fatigue life estimation. Fatigue crack propagation law based on RPG load is

$$da/dN = c(\Delta K_{\mathrm{RPG}})^m, \tag{1}$$

   where $c = 4.5 \times 10^{-11}$, $m = 2.7$, unit in ΔK_{RPG} corresponds to $\mathrm{MPa}\sqrt{\mathrm{m}}$. These material constatns can be applied to the rolled steels [4].
2. Fatigue crack growth can be simulated in sound welded joints. The beahvior, whcich the tip of cyclic plasticity region is fixed during the fatigue crack initiates and propagates in the first grain, is considered in order to establish the scheme for the estimation of the fatigue crack initiation life.
3. The effect of loading histories applied to structures can be taken into consideration quantitatively for the fatigue crack growth estimation.
4. The effect of the pre-existing residual stresses and the dead load (mean stresses) for the fatigue life can be considered.
5. The fatigue crack growth curve as a function of the number of cycles can be calculated.
6. Material constants and other coefficients are less than in other fatigue crack growth simulation codes. All the costants and coefficients in FLARP have physical meaning [2].

The validity of the fatigue life estimation by FLARP is investigated in this paper by comparing the estimated S-N curves by FLARP with the experimental results. The fatigue test results for in-plane gusset welded joints [5] are applied as the reference data. Although the in-plane joint type is very popular and used in many steel structures, few research reports on their fatigue performance are published.

FATIGUE LIFE ESTIMATION FLOW BY FLARP

The fatigue life estimation procedure by FLARP is shown in figure 1 and summarized belows.

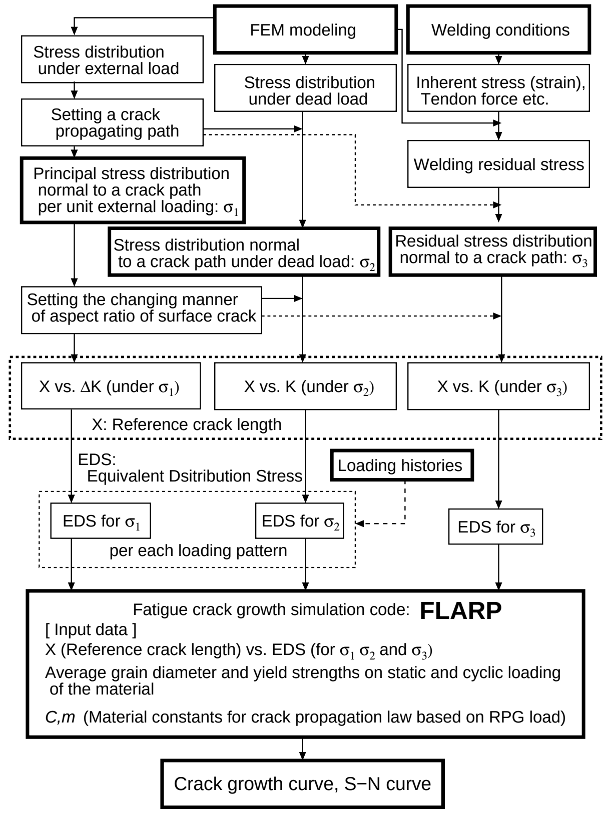


Figure 1. CALCULATION FLOW OF FLARP

1. Calculation of the stress distributions around the fatigue crack growth region under the unit external stress amplitude, the dead load (mean stress) and the pre-existing residual stress field by numerical analyses, e.g. FEM.
2. Identification of the fatigue crack propagation path. The fatigue crack propagates normal to the direction of the applied maximum principal stress [6].
3. Calculation of the normal component of stresses along the assumed crack path.
4. Estimation of the change of aspect ratio of the fatigue surface crack. The shape of the fatigue crack can be approximated to an ellipse until full penetration of the wall thickness. This period corresponds to a substantial proportion of the total fatigue life. The changing manner of the aspect ratio of surface cracks near a fillet weld toe in the as-welded condition is proposed in Ref. [4].
5. Calculation of stress intensity factors under each stress distribution. In these calculations, the girth length of the assumed crack path replaces the straight line for the convenience. The stress intensity factors for a surface cracked body under arbitrary applied stresses can be approximated by using the improved superposition method [4] based on

Table 1. WELDING CONDITIONS AND YIELD STRESS

Specimen Type	GS	GL
Current [A]	110-120	160-175
Voltage [V]	25	25
Travel speed [cm/min]	9.5	14
Yield stress [MPa]	402	402

the method proposed by Maddox [7]. The reference crack length (X in figure 1) is defined as the deepest crack depth in the case of a surface crack and as the crack length in case of a through thickness crack.

6. Transformation of the each stress distribution into the Equivalent Distribution Stresses (EDS in figure 1). EDS corresponds to the stress distribution normal to the crack surfaces of a through-thickness crack in an infinitely wide plate and gives the same stress intensity of the objects. FLARP adopted EDS in order to avoid the surface crack growth simulation directly. FLARP is based on the cohesive force model and no cohesive force model to be able to apply the surface crack at present.
7. Fatigue crack growth simulation by FLARP.

SUMMARY OF THE EXPERIMENTS

Fatigue tests in in-plane gusset joint specimens under constant amplitude loading (frequency 10Hz) were reported in Ref. [5]. Two different size specimens shown in figure 2 were used.

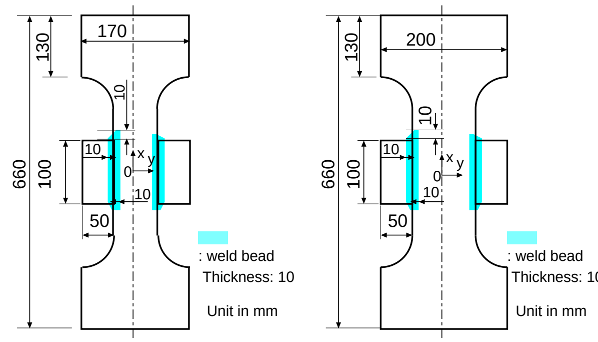
The applied minimum stresses for specimen GS and GL are equal to 10MPa.

Gussets were connected to the main plate by making a single bevel weld using four weld passes. All of the specimens were in the as-welded condition. The welding condition and yield stress under monotonic static loading for each specimen are shown in table 1.

Although yield stresses under cyclic loading are necessary in order to simulate the fatigue crack growth by FLARP, no date are reported in the reference. The ratio of the yield stress under static to the under cyclic loading was investigated. The ratio is equal to 0.545 in mild steel [4]. Thus, yield stresses under cyclic loading for each specimen were estimated by multiplying the each yield stress under static loading by 0.545.

RESIDUAL STRESS DISTRIBUTIONS

Most of fatigue cracks in the steel welded structures initiate from the weld toe. Tensile welding residual stresses, whose peak value reaches yield stress in mild steel and 500MPa in high tensile steel, exist in the crack initiation region. It is considered



(a) GS (b) GL

Figure 2. SPECIMEN CONFIGURATIONS

that tensile residual stresses reduce the fatigue life. On the other hand, the fatigue crack propagation rate decreases under compressive residual stresses. The welding residual stresses in each specimen should be obtained quantitatively in order to estimate the fatigue crack growth. The residual stresses in each specimen were estimated by finite element analyses with the inherent stress method [8] as the source of residual stresses, because no residual stress distribution is shown in the reference.

The inherent stress generated by welding is formulated as a function of the heat input and the material yield strength. In the case of in-plane gusset weld joints, the inherent stress should be given in consideration of the specimen geometries and the flush weld (boxing weld near the edges).

The inherent stress generated by butt welding (σ^{Ia}) is formulated in equation (2) [9]:

$$\begin{aligned}
\sigma^{Ia}(x,y,z) &= \int_0^L g(\xi(\ell)-x,\eta(\ell)-y,z)d\ell, \qquad (2)\\
g(x,y,z) &= \alpha\sigma_Y \exp(-\pi(x^2+y^2)/B^2)h(z:T)/B,\\
h(z:T) &= \sum_{n=0}^{\infty} \exp(-\pi(\lambda y_n/B)^2),\\
y_n &= |y+\{(-1)^n(n+0.5)-0.5\}T|,\\
B &= \beta\sqrt{\gamma Q/\sigma_Y},
\end{aligned}$$

where, $\alpha = 1.942$, $\beta = 1.357$, $\gamma = 0.2$, $\lambda = 1.788$.

ℓ: coordinate system along the weld line ($0 \le \ell \le L$),
$\xi(\ell)$, $\eta(\ell)$: coordinates on the weld line,
Q: heat input,
T: plate thickness.

The inherent stress generated by boxing welding (σ^{Ib}) is formulated in equation (3) [10]:

$$\sigma^{Ib}(x,y,z) = \alpha\sigma_Y \exp(-\pi(x'/B)^2)h(|y'|:T), \qquad (3)$$

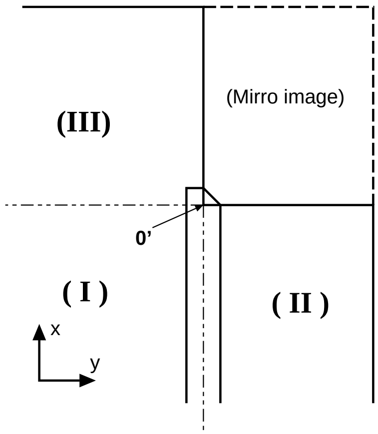


Figure 3. REGIONS IN WHICH THE DIFFERENT INHERENT STRESS DISTRIBUTIONS ARE APPLIED

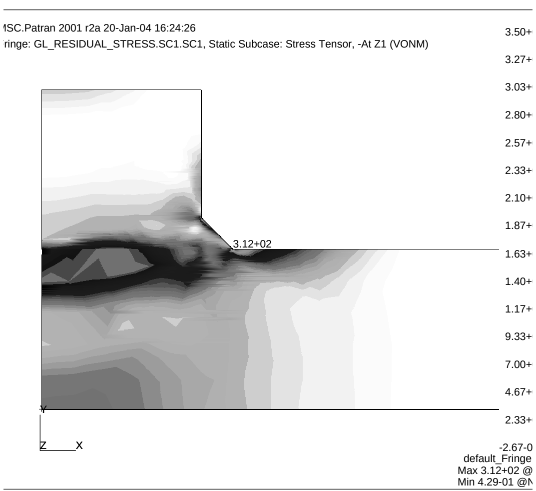


Figure 4. RESIDUAL STRESS DISTRIBUTION (VON MISES EQUIVALENT STRESS)IN SPECIMEN GL BY FINITE ELEMENT ANALYSIS

where,

(x', y'): coordinates which the origin is shown as 0' in figure 3,

λ: 2.195.

The inherent stresses (σ^I) in the region (I), (II) and (III) shown in figure 3 can be obtained as follows. The superposition rule for the inherent stress was introduced in Ref. [10].

Region(I) and (II) $\sigma^I = \max(\sigma^{Ia}, \sigma^{Ib})$

Region (III) $\sigma^I = \max(\sigma^{Ia} + \sigma^{Ia'}, \sigma^{Ib})$, where $\sigma^{Ia'}$ corresponds to the additional inherent stress caused by the mirror effect for the free edge (drawn by dashed line in figure 3).

Calculations are performed by the finite element code, MSC Nastran 2001. σ_I is inputted into the code as the source of residual stresses.

Figure 4 is an example of the calculated residual stress distribution (von Mises equivalent stress) in specimen GL. The analyses are performed for one quarter of the spceimen because of the symmetry of the specimen configuration.

CALCULATION OF FATIGUE LIFE BY FLARP

Fatigue life estimations for each specimen are performed by FLARP.

Crack Propagation Paths

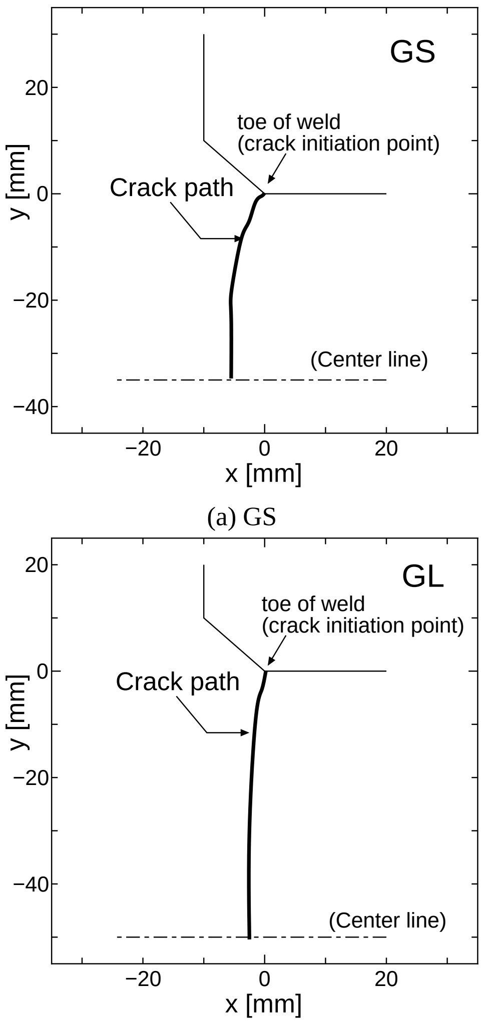
Crack propagation paths for each specimen are shown in figure 5. The fatigue crack start point on each specimen is assumed to be the weld toe where shows the maximum value of the principal stress occurs. The stress distributions associated with the applied external unit amplitude loading (solid line and circle) and the welding residual stress (dashed line and triangle) at the assumed crack path in each specimen are shown in figure 6. These stresses are calculated by MSC Nastran 2001. The same finite element mesh idealization was used for the external stress amplitude loading and the residual stresses in each specimen.

Detailed stress distributions near the crack initiation region under the external unit stress amplitude are estimated by using the formula for the stress distribution near a notch root [11]. The root radii of the weld toe in each specimen are set at 0.5mm in specimen GS and 0.3mm in specimen GL. Residual stresses near the crack initiation region are estimated by smooth extrapolation from the results of the finite element analyses.

Aspect Ratios for surface fatigue cracks

Generally, fatigue cracks initiate as maltiple surface cracks from sound stress concentration sites at an early stage of the component life. Surface cracks coalesce into one large surface crack. This surface crack penetrates through the plate thickness and develops into a through-thickness crack. Because this process is very complex and it is not possible to perform the numerical simulation of this surface type fatigue crack growth process at present, multiples surface cracks were replaced a single surface crack and the changing aspect ratio of the single surface crack evaluated. Detailed explanation of this method is introduced in Ref. [4].

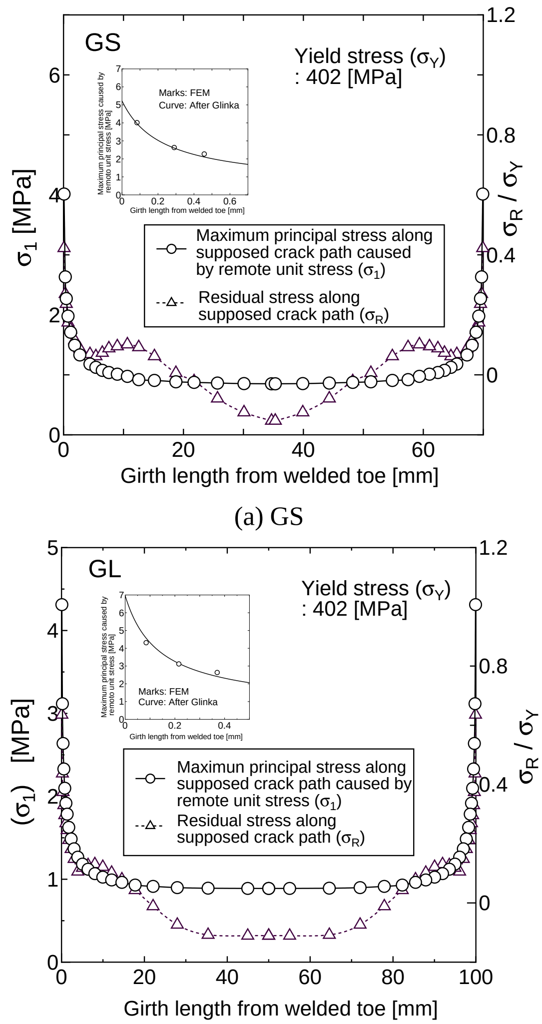
The predicted aspect ratios for surface cracks in each specimen are shown in figure 7. The average grain diameter of the materials used was assumed to be 30μm. This value seems to be valid because fatigue life is not affected when the average grain diameter is larger than 20μm, even though 30μm is a little smaller than the average grain diameter of steels.



(a) GS

(b) GL

Figure 5. ASSUMED FATIGUE CRACK GROWTH PATHS



(a) GS

(b) GL

Figure 6. STRESS DISTRIBUTIONS AT THE ASSUMED FATIGUE CRACK PATH

The changes of aspect ratio in each specimen are similar, because the stress gradient dominates the aspect ratio and the stress gradients in the two specimens are similar.

Stress Intensity factors

Stress intensity factors for the external unit loading and the residual stresses in each specimen are calculated as a function of the reference crack length (X). These results are shown in figure 8. Solid lines in figure 8 represent the stress intenisty factors for the external unit loading and dashed lines correspond to the stress intensity factors for the residual stresses.

Stress intensity factors for surface cracked body under arbitrary applied stresses are calculated by the superposition procedure [4]. Stress intensity factors for a through-thickness crack in each specimen were calculated by the integration of a single edge crack subjected to concentrated forces on the crack surfaces [12] which were represented by stress distributions over the crack surfaces.

The region where stress intensity factors change drastically corresponds to the transition region from the surface crack to the through thickness crack.

Equivalent Distribution Stress

The Equivalent Distribution Stress (EDS) corresponds to the stress distribution over the crack surfaces of a through-thickness crack in an infinitely wide plate and gives the same stress intensity factor. EDS is inputted into FLARP in order to perform

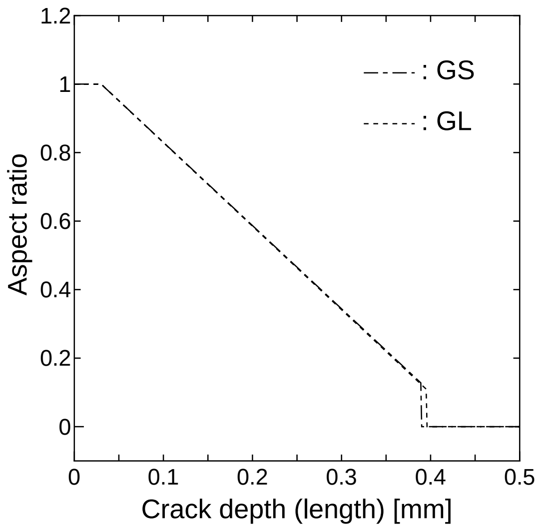
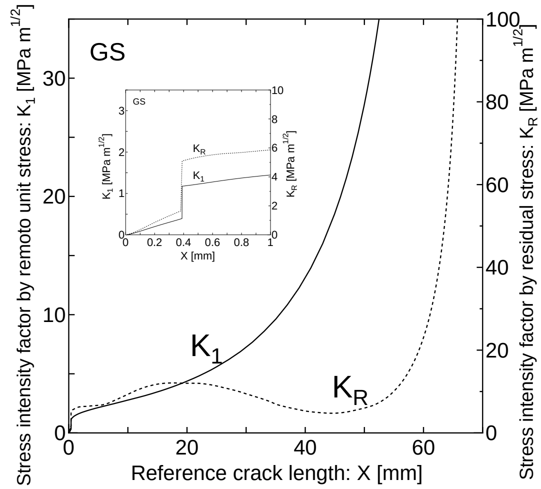
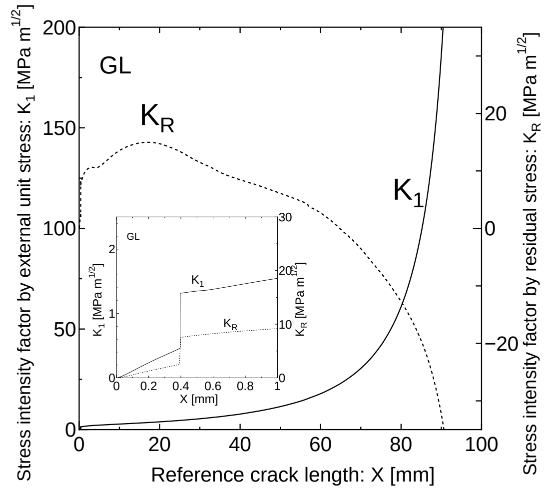


Figure 7. ASSUMED CHANGE OF FATIGUE SURFACE CRACK ASPECT RATIO



(a) GS



(b) GL

Figure 8. RELATION BETWEEN REFERENCE CRACK LENGTH (X) AND STRESS INTENSITY FACTORS

fatigue crack growth simulations.

Calculation results for EDS in each specimen are shown in figure 9. The relationships between the reference crack length and the stress intensity factor shown in figure 8 are used as input data for figure 9. Solid lines in figure 9 represent EDSs under external unit loading and dashed lines correspond to the EDSs under residual stress fields.

Calculation Results and Discussion

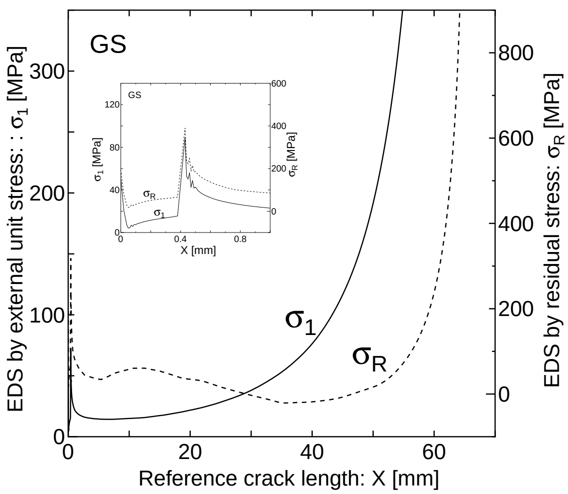
Fatigue crack growth simulations for each specimen are performed by FLARP. Examples of crack growth curves for each specimen are shown in figure 10. The period from crack initiation to crack penetration through the plate thickness direction corresponds to most of the total fatigue life. All the simulations show similar results. It is considered that small EDSs during surface crack growth prolong the total fatigue life in each specimen.

Comparison of estimated $S-N$ curves by FLARP with experimental data for each specimen are shown in figure 11. The crack depth for the fatigue crack initiation life in figure 11 corresponds to the average grain diameter of the materials, which is equal to 30μm in these simulations.

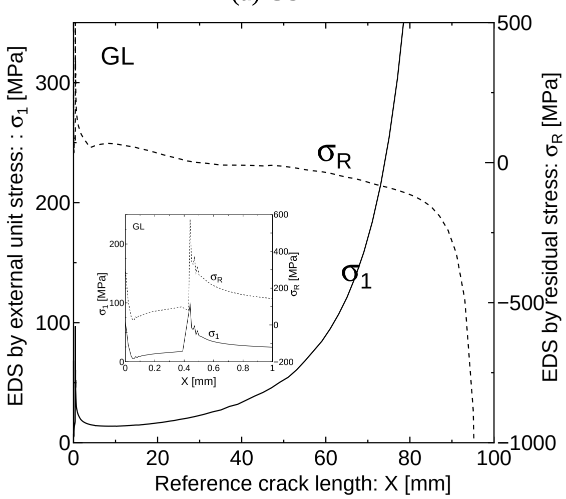
Fatigue limits in each specimen were estimated to be about 80MPa for specimen GS and about 60MPa for specimen GL from the fatigue tests. FLARP enables the estimation of the state of a non-propagating crack after initiation as well as the crack propagation. The estimated fatigue limit is 85MPa for specimen GS and 60MPa for specimen GL. These results are in good agreement with the experimental ones.

Although the slopes of estimated $S-N$ curves for the specimens are similar to those for the experimental results, the estimated fatigue lives are longer than the experimental ones. It is considered that the differences arise for the following reasons:

1. Inaccuracy of the yield stresses under both cyclic and static loadings. The yield stress under cyclic loading affects the fatigue crack initiation life and that under static loading affects the propagation life.
2. Inaccuracy of the coefficients in the fatigue crack propagation law based on ΔK_{RPG}.These coefficients were assumed to the same as those for welded rolled steel structures reported [4], because no information for the coefficients was reported.
3. Variation of the average grain diameter in the specimen materials. The grain diameter affects the fatigue life and the

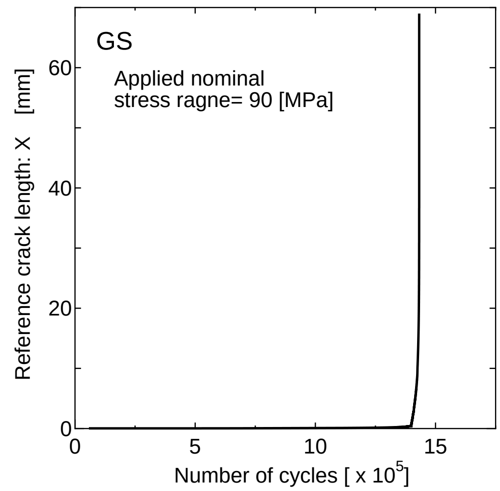


(a) GS

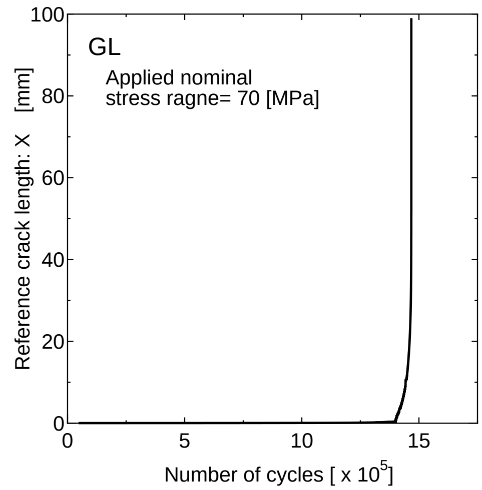


(b) GL

Figure 9. EQUIVALENT DISTRIBUTION STRESSES (EDS)



(a) GS (Stress range: 90MPa)



(b) GL (Stress range: 70MPa)

Figure 10. EXAMPLES OF CALCULATED CRACK GROWTH CURVE

fatigue limit.

It is considered that the results of the FLARP fatigue crack growth simulation will be improved by using more accurate material constants.

CONCLUSION

Many conventional fatigue strength evaluation methods do not give accurate fatigue crack growth predictions, because the present state of the fatigue strength evaluation in many desigin criteria is so-called "Go or Non-go" criteria based on the $S-N$ curves. The authors have established the algorithm which enables simulation of the fatigue crack growth from the stress concentration field with zero defect and have subsequently developed the program code "FLARP" based on this algorithm.

The validity of the fatigue life estimation by FLARP is confirmed by comparing the estimated S-N curves with the experimental results for in-plane gusset welded joints. The $S-N$ curves by FLARP compare to the experimental results. It is considered that the differences that arise the both results are caused by the inaccuracy of the material constants and that the simulation results by FLARP will be improved by using more accurate material constants.

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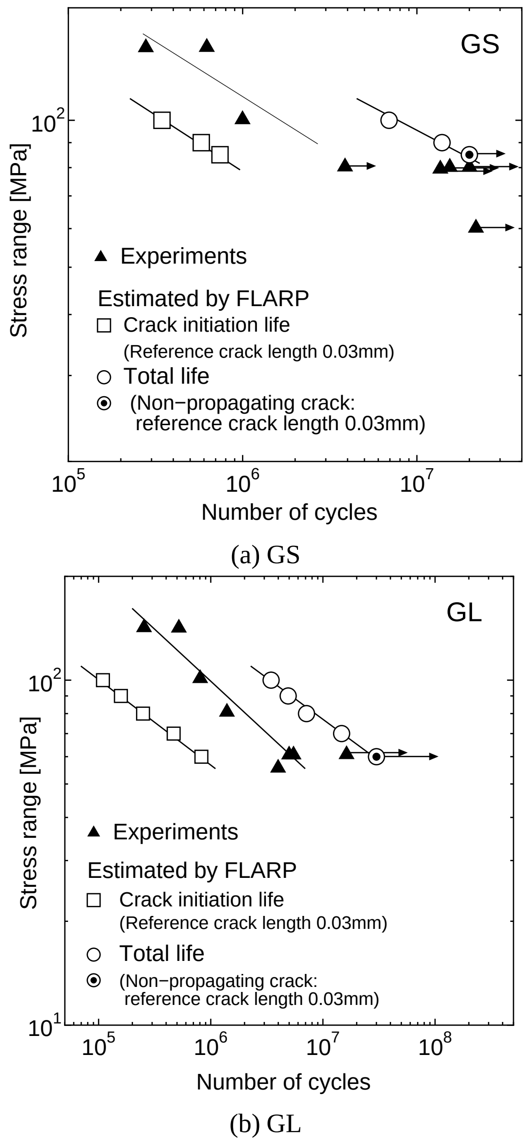

Figure 11. COMPARISON OF ESTIMATED $S-N$ CURVES BY FLARP WITH EXPERIMENTAL DATA

REFERENCES

[1] Toyosada, M. and Niwa, T., The Significance of RPG load for fatigue crack propagation and the development of a compliance measuring system, International Journal of Fracture, Vol.67, 1994, pp.217-230

[2] Toyosada, M., Gotoh, K. and Niwa, T., Fatigue Crack Propagation for a Through Thickness Crack: A crack propagation law considering cyclic plasticity near the crack tip, International Journal of Fatigue, 2004,(Now on printing)

[3] Toyosada, M., Gotoh, K. and Niwa, T., Fatigue Life Assessment for Welded Structures without Initial Defects: An Algorism for Predicting Fatigue Crack Growth from a Sound Site, International Journal of Fatigue, 2004,(Now on printing)

[4] Toyosada, M. and Niwa, T., Prediction of fatigue life for steel structures, (in Japanese), ISBN 4-320-08135-8, Kyouritsu shuppan Co. Ltd., 2001, and http://www.nams.kyushu-u.ac.jp/common/production /fatigue/fatigue.html (in English)

[5] Kondo, A. and Yamada, K., Fatigue tests by long-time variable amplitude loading (in Japanese), Fatigue Strength Research Committee in Japan Welding Society, 2001, FS-1044-01

[6] SR169 Committee, Final report of SR169 Committee (in Japanese), The Shipbuilding Research Association of Japan, 1981
Erdogan, F. and Sih, G. C., On the Crack Extension in Plates Under Plane Loading and Transverse Shear, Transactions of ASME, Journal of Basic Engineering, Vol.85, pp.519-527

[7] Maddox, S.J., An Analysis of Fatigue Cracks in Fillet Welded Joint, The Welding Institute, 1972, E/49/72

[8] Matsuoka, K., An Analytical Method on Residual Stresses in Welded Built-up Shell Structures (in Japanese), Journal of the Society of Naval Architects of Japan, Vol.153, 1983, pp.210-217

[9] Matsuoka, K. and Yoshii, T., Weld Residual Stress in Corner Boxing Joints, NK TECK BULLETIN, 1996, pp.1-10

[10] Matsuoka, K., Takahashi, I., Yoshii, T., Iidaka, H. and Fujii, E., Effects of Plate Thickness and Heat Input on Fatigue Strength of Non-Load-Carrying Fillet Welded Joints, IIW Doc. XIII-1407-91, 1991

[11] Glinka, G., Calculation of Inelastic Notch-Tip Strain-Stress Histories under Cyclic Loading, Engineering Fracture Mechanics, Vol.22, No.5, 1985, pp.839-854

[12] Tada, H., Paris, P.C. and Irwin, G.R., The Stress Analysis of Cracks Handbook (Second Edition), Del Research Corporation, 1985