FATIGUE LIFE PREDICTION OF WELDED MEMBERS BASED ON DAMAGE MECHANICS

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INTRODUCTION

Decision concerning the maintenance of the existing bridges gives serious impact on economy of the surrounding community. Thus, it is important to extend the lifetime of bridge structures and evaluate the fatigue damage accurately. In case of steel bridge, structures are commonly fabricated by welding. These welded structures are often subjected to high cyclic loading and fatigue damage occur at the welded joints. In this study, the fatigue life prediction of welded structures is carried out by using continuum damage mechanics (CDM)[1]. For high cycle fatigue (HCF), it is considered that the plastic deformation and damage occurs at the micro-scale. Therefore, the two-scale model presented by Lemaitre [2] is applied to evaluate damage evolution. The effect of residual stress on fatigue behavior of welded structures is also considered by using the inherent strain method[3)4)]. It is confirmed that the proposed method could give the reliable fatigue lifetime of welded structural members[5)].

FATIGUE ANALYSIS METHOD

The HCF life prediction of welded members are performed by two steps: 1) Estimate the welding residual stresses by using the inherent strain method. 2) Perform fatigue damage analysis based on CDM with considering the effect of residual stress.

Determination of Residual Stresses[3)4)]

A simplified method for evaluating the residual stresses in welded structures is applied. The internal stress σ_{ij}^0 is considered as the residual stresses in the weldment. The total strains ε_{ij} are the sum of elastic strains ε_{ij}^e and inherent strains ε_{ij}^* as

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^* \tag{1}$$

and the constitutive equation is written as: $\sigma_{ij}^0 = E_{ijkl}\varepsilon_{kl}^e = E_{ijkl}(\varepsilon_{kl} - \varepsilon_{kl}^*)$ (2)

The residual stresses are the self-equilibrium stresses with no external forces, thus the force equilibrium condition is given as

$$\sigma_{ij}^0 n_j = (E_{ijkl}\varepsilon_{kl})n_j - (E_{ijkl}\varepsilon_{kl}^*)n_j = 0 \quad \text{and} \quad \sigma_{ij,j}^0 = (E_{ijkl}\varepsilon_{kl})_{,j} - (E_{ijkl}\varepsilon_{kl}^*)_{,j} = 0 \tag{3}$$

where E_{ijkl}: elastic modulus, n_j: unit normal vector. The inherent strains for butt weld, T-joint and I-joint are calculated by the simplified equations[3)4)]. The residual stresses can be evaluated by the elastic finite element analysis based on above equations.

Continuum Damage Mechanics[1)2)]

The basic concept of CDM considers the damage variable as the degree of degradation of material in the homogeneous field. Thus, the basic image of damage variable D is defined as the loss of effective area in the representative volume element (RVE).

$$D = \frac{A_D}{A_0} \tag{4}$$

where A_0: the total area of considered plane, A_D: the area of all micro-defects.

For high cycle fatigue, it is considered that damage and plasticity occur at the micro-scale μ. Thus, the two-scale model [2)] is applied to evaluate the damage evolution in a weak micro-inclusion embedded in a RVE. The damage evolution is derived from the associated flow rule with the strain energy density release rate Y^μ and the potential of dissipation F_D^μ based on the thermodynamics at the micro scale. Then, it is assumed to be proportional to the increment of accumulated plastic strain dp^μ as

$$dD = \frac{\partial F_D^\mu}{\partial Y^\mu} d\lambda^\mu = \left(\frac{Y^\mu}{S}\right)^n dp^\mu \tag{5}$$

where S *and* n: the damage energy strength and exponent of damage evolution, respectively.

The damage occurs when p^μ reaches a certain value p_D and the macrocrack initiated when D reaches the critical value Dc. The stresses at micro-scale σ_{ij}^μ are evaluated from the stresses at macroscale σ_{ij} by mean of the self-consistent scheme [2)].

The constitutive equations of the elasto-plastic couples damage at the microscale with considering the yield criterion that applies the Kinematic hardening X^μ and considers yield stress σ_y^μ equal to fatigue limit σ_f.

$$f^\mu = \left(\sigma^{\mu D}/(1-D) - X^{\mu D}\right)_{eq} - \sigma_f \tag{6}$$

Finally, it is possible to compute damage evolution at the micro-scale as a function of the macro stresses for any loading.

Table 1. Material properties

Material properties	*Symbol*	*Base metal*	*Weld & HAZ*
Elastic modulus (MPa)	E	2x10^5	2x10^5
Poison's ratio	ν	0.3	0.3
Fatigue limit stress (MPa)	σ_f	160	220
Yield stress (MPa)	σ_y	330	520
Ultimate stress (MPa)	σ_u	465	650
Critical damage	D_C	0.9	0.9
Hardening parameter(MPa)	C	470	500
Micro-crack closure	h	0.2	0.2

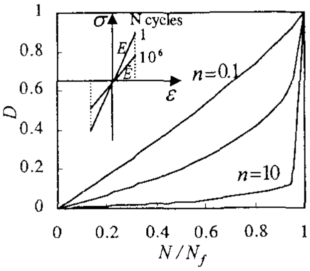


Fig. 1 Damage curves identify n

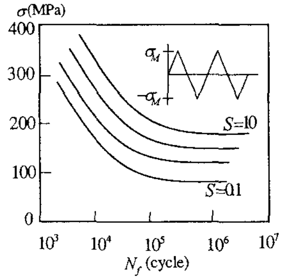


Fig. 2 S-N curves identify S

Identification of Material Parameters[2) 5)]

The simplified identification of the main parameters, damage energy strength S and exponent n in **Eq. (5)**, is proposed by using **Eq. (7)** and **Eq. (8)**, which obtained from the two scale model with the assumption: $h= 1, p_D=0, D=1$.

$$N_f = \frac{(2ES)^n C}{2(R_v^{\mu})^n\left[\left((\sigma_M + k\sigma_f)/(1+k)\right)^{2n+1} - \sigma_f^{2n+1}\right]} \tag{7}$$

where N_f: number of cycle to failure; R_v^{μ} : stress triaxiality function ; σ_M: applied stress; $k=3aE/2C$; C: hardening parameter.

$$D = 1 - \left[1 - (N/Nf)\right]^{\frac{1}{2n+1}} \tag{8}$$

The damage exponent n can be identified by inverse calculation of **Eq. (8)** with the HCF damage test data (**Fig. 1**). Subsequently, the damage energy S can be given explicitly by using **Eq. (7)** with S-N curve test data (**Fig.2**).

NUMERICAL ANALYSIS AND RESULTS

The HCF damage analysis and life prediction of a T-joint is demonstrated by the proposed method. The T-joint geometry and FE-mesh is shown in **Fig. 3**. The material properties for base metal, weld and HAZ are shown in **Table 1**,respectively.

Residual Stress

The residual stress distribution of T-joint in the flange and web are obtained as **Fig. 4(a)** and **4(b)**, respectively. It is confirmed that the analysis results agree well with the experiment [4)].

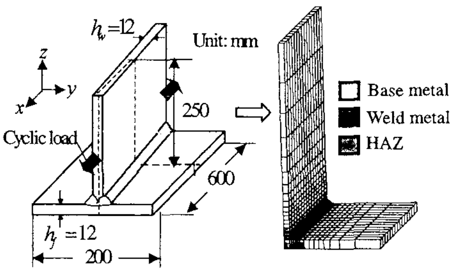
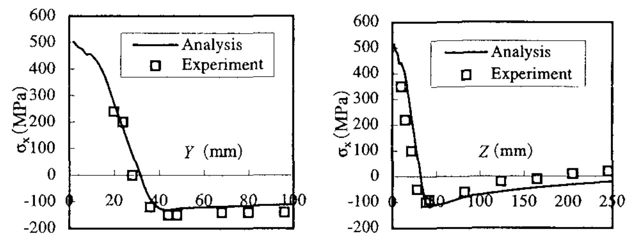


Fig. 3 Analysis model of T-joint



(a) flange **(b)** web

Fig. 4 Residual stress distribution

Fatigue Life Prediction

The damage exponent n=2 for all materials and damage energy S=2.0MPa and 6.0MPa for base metal, weld and HAZ, respectively are obtained by the simplified method. The HCF damage analysis and life prediction of T-joint under constant amplitude cyclic loading is performed until the failure condition satisfied. The crack area (critical damaged zone, • in **Fig. 5**) completely spreads through the longitudinal cross-section of T-joint, is considered to be the failure condition. **Fig. 6** shows The damage evolution at the weld zone with applied stress range $\Delta\sigma$. The comparison of fatigue life prediction with the experimental results from JSSC[6)] is shown in **Fig. 7**. It is observed that the proposed method can predict the lifetime accurately.

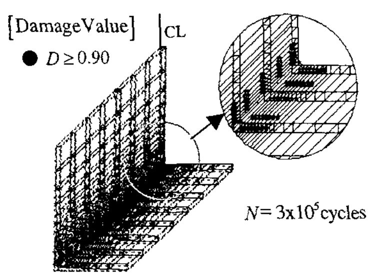


Fig. 5 Damage distribution

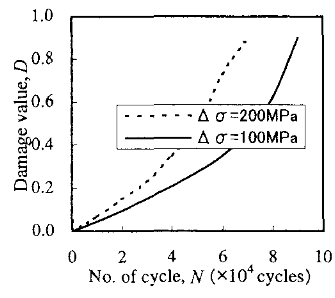


Fig. 6 Damage evolution

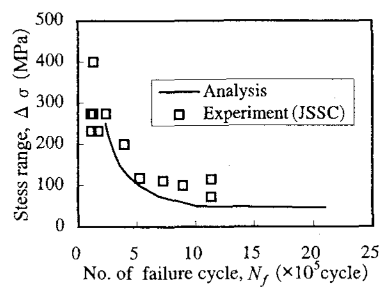


Fig. 7 Fatigue life prediction

CONCLUSIONS

The HCF damage analysis of a welded member based on the CDM was performed with considering the effect of the residual stresses. From the analytical results, it is confirmed that the HCF damage analysis and life prediction of typical welded structure under constant amplitude loading could be simulated by the proposed method. In order to obtain the arculate fatigue life for the practical application, the identification of material parameters needs to be improved. Furthermore, the investigation of fatigue behavior under variable amplitude loading and definition of failure condition should be studied.

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