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Study on Energy-Based Fatigue Damage Model for Life Prediction under Creep-Fatigue

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1. Introduction

High temperature pressurized plant components such as boiler header, superheater and pipe are exposed to creep-fatigue loading during operation. In these plant components, crack initiates and propagates because of creep-fatigue loading. Stress level near crack increases because of crack initiation and growth and it makes load sequence near crack complex.

Conventional fatigue damage model, as known as Miner damage model, calculates damage from applied strain range. On the other hands, energy-based fatigue damage model calculates the damage from applied strain energy, which is more sensitive to load sequence.

In the situation that applied load sequence is very complex because of crack initiation and growth, energy-based fatigue damage model may be a better option than conventional damage model. Hence, in this study, we validated and compared the energy-based fatigue damage model with conventional fatigue damage model, conducting finite element damage analysis on creep-fatigue test of P91 at 600 ^{o}C.

2. Creep-Fatigue Damage Models

In this study, creep-fatigue damage model is used to quantify damage under creep-fatigue loading. The failure criteria using the creep-fatigue damage model is given below [1]:

$$D_d + D_c + D_f = 1 \text{ (at failure)} \quad (1)$$

D_d is ductile damage, D_c is creep damage and D_f is fatigue damage. Eqn. (1) is valid for most of metallic materials [1]. Increments of ductile and creep damages are calculated using equations below:

$$\Delta D_d = \frac{\sigma_e \Delta\varepsilon_{in}^{\max}}{W_{f0}} \quad (2)$$

$$\Delta D_c = \left(\frac{1}{W_f(\dot{W}_{in})} - \frac{1}{W_{f0}}\right)\Delta W_{in} \quad (3)$$

σ_e is equivalent stress, $\Delta\varepsilon_{in}^{max}$ is maximum inelastic strain increment and ΔW_{in} is inelastic strain energy increment. W_{f0} and $W_f(W_{in})$ are upper-bound fracture strain energy and rate-dependent fracture strain energy function, respectively, which are material-dependent constant and function. Conventional fatigue damage model, as known as Miner damage model, calculates damage increment using equation given below:

$$\Delta D_f = \frac{1}{N_{f0}(\Delta\varepsilon_{in})} \quad (4)$$

N_{f0} is fatigue life and $\Delta\varepsilon_{in}$ is inelastic strain range. The energy-based model calculates damage from strain energy, as equation given below:

$$\Delta D_f = \frac{\Delta W_{in}}{W_f(\Delta\varepsilon_{in})} \quad (5)$$

$W_f(\Delta\varepsilon_{in})$ is strain-range-dependent fracture strain energy suggested by Lefebvre and Ellyin [2], which can be determined from cyclic test data.

3. FE damage analysis method

FE damage analysis on creep-fatigue test of P91 is conducted to validate energy-based fatigue damage model. Mono-element analysis is conducted using Abaqus 2018 with user-subroutines USDFLD and CREEP. Quasi-dynamic analysis method using *VISCO option supported by Abaqus 2018 is used.

As material constitutive model of P91 at 600 ^{o}C, nonlinear combined hardening model determined by Saad [3] and creep deformation model suggested by Takahashi [4] are used.

To calculate damage during FE analysis using creep-fatigue damage model given in section 2, user-subroutine USDFLD and CREEP are used.

4. Results

Analyzed test cases are given in Table 1, which are creep-fatigue/creep and creep-fatigue/fatigue tests using smooth bar specimens conducted by Takahashi [1]. Detail description of the tests are given in reference [1].

Simulated deformation behavior for CF-C2 test are given in Fig. 1. As shown in Fig. 1, FE results are overall in good agreement with test results.

Calculated damages are given in Fig. 2. In CF-C test cases, energy-based fatigue damage is greater than conventional fatigue damage. On the other hands, in CF-F test case, conventional fatigue damage is greater than energy-based fatigue damage. However, these differences are not critical; maximum error is about 5 %. The difference of damage calculation under creep-fatigue between Miner damage model and energy-based damage model arises from fatigue fracture energy, $W_f(\Delta\varepsilon_{in})$ in Eqn. (5) based on pure fatigue, because the shape of hysteresis loop of creep-fatigue is different to that of pure fatigue.

Table 1 Analyzed test conditions [1]

Test type	**Test no.**	**Creep-fatigue condition**	**Creep or fatigue condition**
Creep-fatigue /creep	CF-C1	0.5% strain range 0.167h hold time 1000 cycles	140 MPa creep stress 837.2 h rupture time
	CF-C2	0.5% strain range 1.0h hold time 1000 cycles	140 MPa creep stress 405.6 h rupture time
Creep-fatigue /fatigue	CF-F1	0.5% strain range 1.0h hold time 1000 cycles	0.5% strain range 3098 cycles to failure

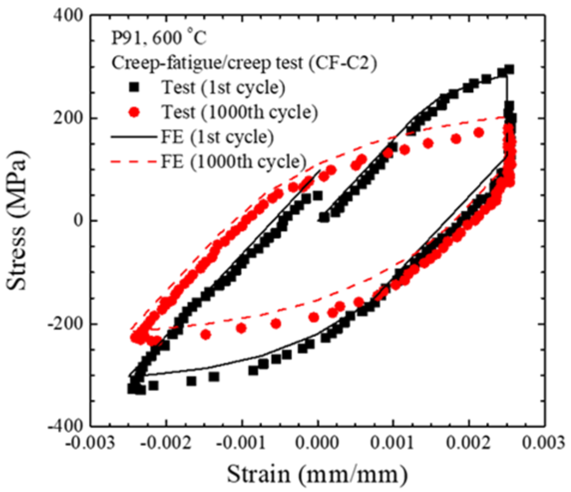

Fig.1 Simulated deformation behavior for CF-C2 test case

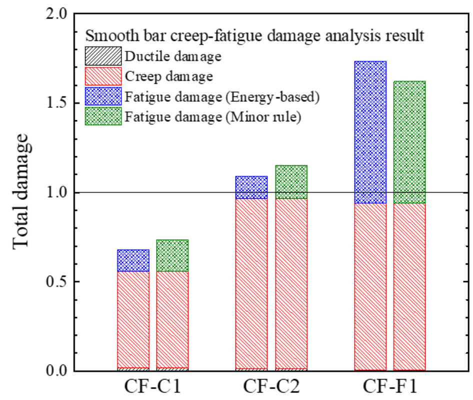

Fig.2 Result of damage analysis on creep-fatigue tests

5. Conclusion

In this study, energy-based damage model for creep-fatigue life prediction was validated and compared with conventional damage model, as known as Miner damage model. Following conclusions are made through this study.

(1) There is difference in fatigue damage calculation under creep-fatigue between energy-based and conventional fatigue damage model. However, it is not critical. Energy-based damage may be an option for creep-fatigue life prediction when considering complex loading sequence caused by crack growth.

(2) However, the number of test cases considered in this study is just three. More tests and damage analysis are needed for validation of energy-based fatigue damage model.

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