Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

# Demonstration of creep-fatigue life assessment procedures by structural model tests

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ABSTRACT: In the structural design of fast reactors operated at about 550°C, estimation of inelastic deformation and resulting damage is essentially important. In many structural design codes, a large emphasis was placed on the procedures for assessing structural integrity from the results of purely elastic stress analysis. As an alternative approach, direct assessment of stress and strain by inelastic analysis has a potential to bring about more reliable and economic component design. The authors have been engaging in the development of a guideline for making design assessment based on inelastic analysis. Inelastic constitutive model and creep-fatigue damage estimation method were developed based on various test data of type 304 and low-carbon 316 steel. A draft guideline was generated and its applicability was demonstrated by a number of structural model tests of various geometries.

## 1. INTRODUCTION

Creep-fatigue failure is one of the principal concerns in the design of components of liquid metal cooled fast breeder reactor (LMFBR) plants because of high coolant temperature and various thermal transients. Methods for preventing failures due to creep-fatigue interaction generally consist of the following processes.

(1) Assessment of stress/strain distribution in inelastically deformed structures
(2) Assessment of fatigue and creep damage
(3) Assessment of failure life

The authors have been conducting extensive studies on these subjects and produced a draft guideline for application of inelastic analysis for design of high-temperature components of LMFBR plants. Various structural model tests have been conducted to demonstrate applicability of the developed guideline to plant components. Some of the results of our early efforts were already published (Yamauchi et al. 1995, Takahashi 1995) and this paper gives an updated summary of our study.

## 2. LIFE ASSESSMENT METHODS

Assessment of stress and strain is necessary as they are principal parameters dominating the fatigue and creep damages. Finite element method is widely used as a simple and powerful engineering tool for obtaining stress and strain distribution in various structures with complex geometry. However, as inelastic deformation occurring during thermal transients as well as steady-state operation can not be neglected in components of LMFBR plants, a simple linear-elastic analysis can not be applied directly. There are basically two routes to assess stress / strain conditions of inelastically deformed bodies.

One is the elastic assessment route in which the finite element calculation is made using purely elastic constitutive relationship and inelastic deformation as well as its influence on stress and total strain is estimated by post-analysis operation. Direct application of rigorous inelastic analysis is naturally an alternative way. The outline of the both procedures applied in this study is described below.

### *2.1 Elastic Assessment Route*

A basic form of the elastic creep-fatigue design route recommended in the design guide for the Japanese prototype fast breeder reactor, Monju (Iida et al. 1987), was used. The procedure consists of the following steps:

(1) Obtain primary plus secondary stress intensity range, $Sn$ by linearlization of through-thickness stress distribution.

(2) Obtain peak stress intensity range, $Sp$, as the stress range at surface.

(3) Obtain elastic stress concentration factor, $K$, by dividing $Sp$ by $Sn$.

(4) Obtain total strain range, $\varepsilon_t$, by

$$\varepsilon_t = K_\varepsilon \frac{S_n}{E} \tag{1}$$

where $K_\varepsilon$ is elastic-plastic strain concentration factor obtained by

$$K_\varepsilon = Max\{(\frac{S^*}{\bar{S}})K^2,\ KK_e'\} \tag{2}$$

$$K_e' = 1+(q-1)\{1-(\frac{3S_m}{S_n})\} \tag{3}$$

where $\bar{S}$ and $S^*$ represent the stress values corresponding to $S_n/E$ and $KS_n/E$, respectively, as defined in ASME Code Case N-47 (1993). $S_m$ is the design stress intensity and $q$ is the elastic follow-up factor. $q$=3 was assumed following the Monju design guide.

(5) Estimate initial stress for relaxation analysis by substituting $\varepsilon_t/2$ into a cyclic stress-strain relation.

(6) Estimate stress relaxation using a creep strain equation with the strain-hardening law. Elastic follow-up is taken into account by

$$\dot{\sigma} = -\frac{E\dot{\varepsilon}_c}{q} \tag{4}$$

(7) Estimate fatigue damage by substituting $\varepsilon_t$ into the fatigue curve at the highest temperature during a cycle.

(8) Estimate creep damage from the relaxing stress and creep rupture property as

$$D_c = \int \frac{dt}{t_R(\sigma)} \tag{5}$$

where $t_R$ is rupture time in the creep test under the stress, $\sigma$.

(9) Estimate the failure life based on the interaction diagram given in ASME Code Case N-47 (1993).

### 2.2 Inelastic Assessment Route

In our draft guideline for application of inelastic analysis to structural design, standard constitutive models were given for two types of austenitic stainless steel, type 304 and low-carbon medium-nitrogen type 316 (designated 316FR) stainless steel. Time-independent plastic deformation and creep deformation are separated and a two-surface plastic constitutive model developed by one of the author for type 304 stainless steel (Takahashi 1991) was employed for the former. A few constants were modified for applying this model to 316FR steel.

It is recommended to estimate creep deformation by creep strain equations with the strain hardening law as in the elastic assessment route. The creep strain equations with three primary creep strain terms were used to fit the creep behavior for wide time range. It was assumed that the hardening was totally reset at the start of each holding period because the reversed plastic strain exceeded creep strain in all structural models studied.

Creep damage was estimated by the following equation according to the modified ductility exhaustion method (Takahashi 1993) recommended in the guideline based on the studies on creep-fatigue life prediction methods for 316FR steel (Takahashi, 1995b).

$$D_c=100\Delta\varepsilon_{in}\frac{\Delta\varepsilon_c}{\delta} \tag{6}$$

where $\Delta\varepsilon_{in}$ and $\Delta\varepsilon_c$ are Mises inelastic strain range and creep strain increment, respectively, for the cycle concerened and $\delta$ is the minimum rupture elongation in the creep tests. The unit of these quantities is mm/mm. It should be noted that $\delta$ has a tendency to increase with the temperature.

Failure life is estimated by the following linear damage summation rule with the fatigue damage obtained from the Mises total strain range:

$$N_f=\frac{1}{D_f+D_c} \tag{7}$$

### 2.3 Estimation of Crack Initiation Life

Definition of crack initiation life is ambigouis without defining crack length at 'initiation'. The life prediction was made for the measured crack size using the relation between life ratio and crack length shown in Figure 1 which was obtained from uniaxial fatigue and creep-fatigue tests for small solid-bar test specimens.

## 3. APPLICATION TO STRUCTURAL MODEL TESTS

### 3.1 Outline of Tests

Five kinds of structural model tests were conducted to study the applicability of the proposed procedures to various conditions. All of the models except one were made of 316FR steel. Thermal transients were cyclically applied to these models by various heating and cooling methods. Maximum temperatures at the points of crack initiation were between 450 and 640°C, most of them being between 550°C and 600°C. Hold periods up to 10 hours were introduced in some cases to give creep damage in addition to the fatigue damage given by thermal cycles. At some intervals, crack lengths were measured at the surface by replication or a microscope.

## 3.2 Comparison between Predicted and Observed Life

As an example, influence of hold periods on the crack initiation life in the smooth cylinder models subjected to movement of axial temperature distribution is given in Figure 2. It can be seen that the failure life decreased with the hold period due to increase of creep damage and the prediction by inelastic analysis followed its tendency fairly well.

Comparison between observed life and predictions by the above two assessment methods for all structural models are shown in Figures 3 and 4. It can be seen that the elastic route procedure gave very conservative results while inelastic route resulted in more realistic life prediction. Considering the fact that large safety margin (20 against average endurance in terms of life) will be introduced in real design assessment, inelastic analysis-based design procedure holds reasonable conservatism.

## 4. CONCLUSION

The present study demonstrated that inelastic analysis-based creep-fatigue design procedure proposed by the authors has reasonable accuracy in predictiing crack initiation life in various structures subjected to thermal transients and hold periods at high temperature.

This study was carried out as a part of the project of Ministry of International Trade and Industry, titled "Verification Tests of Fast Breeder Reactor Technology", which has been conducted since 1987. The authors would like to express their sincere gratitude to members of the advisory committee (chairman : Professor G. Yagawa, University of Tokyo) for their valuable discussions.

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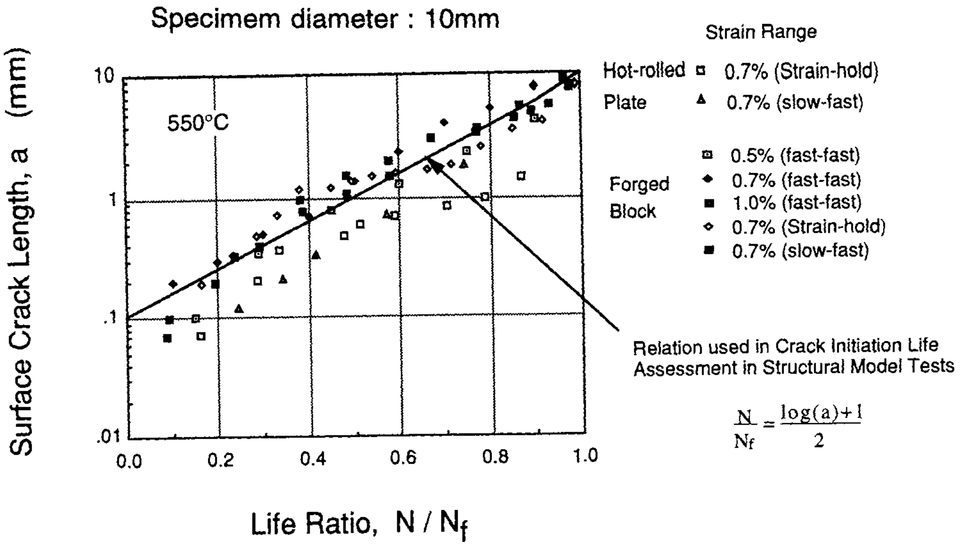

Figure 1 Life Ratio - Crack Length Relation obtained by 316FR Small-size Test Specimens

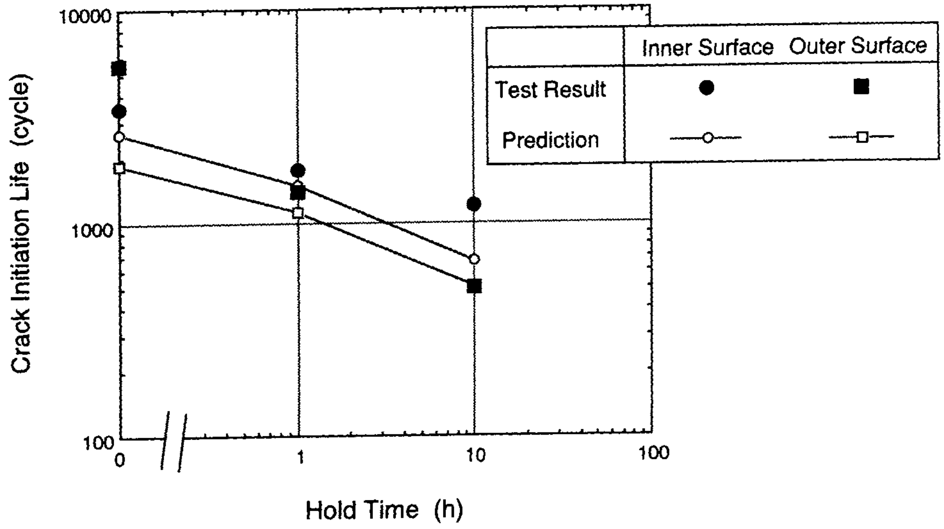

Figure 2 Variation of Crack Initiation Life with Hold Period in 316FR Smooth Cylinder Model

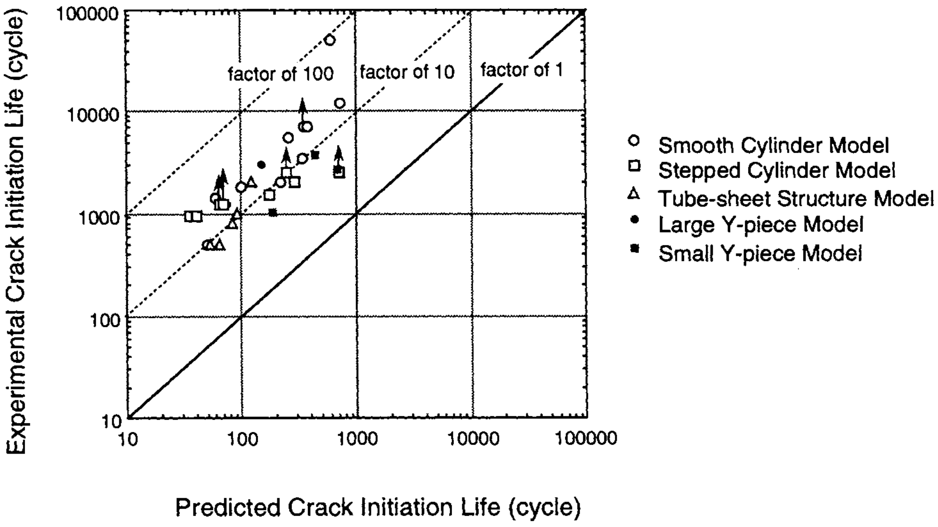

Figure 3 Comparison between Experimental Life and Prediction by Elastic Route Assessment Method

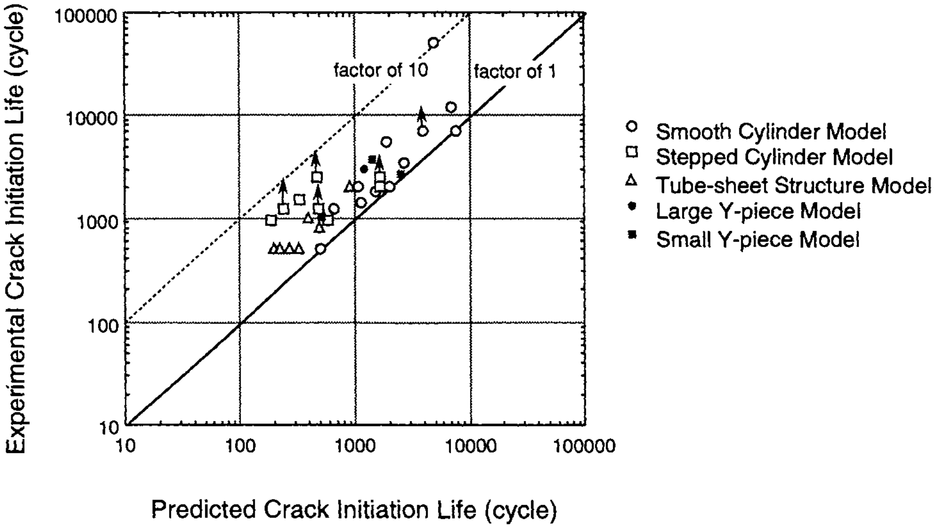

Figure 4 Comparison between Experimental Life and Prediction by Inelastic Analysis-based Assessment Method