Improvement of Structural Integrity Assessment Guideline for Fast Reactor Components - part II: Evaluation of Creep-Fatigue Crack Propagation

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ABSTRACT

In the design assessment of fast reactor plant components, prevention of crack initiation from defect-free structures is a main concern. However, the existence of initial defects such as weld defects can not be entirely excluded and initiated cracks do not lead to component failure instantly. Therefore, evaluation of structural integrity in the presence of crack-like defects is also important to complement the formal design assessment. The authors have been developing a guideline for assessing long-term structural integrity of fast reactor components using detailed inelastic analysis and nonlinear fracture mechanics. This guideline consists of two parts, evaluation of defect-free structures and flaw evaluation. In the latter, creep-fatigue is considered to be one of the most essential driving force for crack propagation at high operating temperature exceeding 500 °C. The uses of J-integral-type parameters (fatigue J-integral range and creep J-integral) are recommended to describe creep-fatigue crack propagation behavior in the guideline. The revision of the guideline was made in March, 2001 based on the new test data and the improvement of estimation methods. This paper gives an outline of the modification of simplified J-evaluation method using reference stress, including the consideration of elastic follow-up.

INTRODUCTION

Structural components used at high temperature must be properly designed to prevent crack initiation during a specified operation period due to creep-fatigue damage with appropriate safety margins. However, the existence of initial flaws such as weld defects can not be completely excluded, and initiated cracks do not lead to instantaneous failure of components. Therefore, evaluation of structural integrity in the presence of crack-like flaws is important to complement the assessment of defect-free structures. When we consider a rational maintenance of components, a fine methodology to estimate crack propagation behavior is also essential to know how a detected flaw is detrimental to continuous operation.

Central Research Institute of Electric Power Industry (CRIEPI) has been conducting a research project on the verification of evaluation method for structural integrity of high-temperature components of fast reactor plants, in which applicability of inelastic fracture mechanics to austenitic stainless steels used in these components has been studied. During the course of the study, a flaw evaluation guideline for fast reactor components was first presented in 1993FY. After that, continuous efforts have been made to improve the applicability and the reliability of the evaluation method [1, 2]. Based on their results, an advanced guideline was generated in March, 2001.

Creep-fatigue is considered to be one of the most essential driving forces for crack propagation at high operating temperature exceeding 500 °C. It was validated that fatigue crack propagation law and creep crack propagation law could be well described by the fatigue J-integral range and the creep J-integral, respectively [3]. The evaluation of the J-integrals for arbitrary crack configuration and arbitrary loading condition can be generally accomplished by detailed numerical analysis such as finite element analysis, however, it is time-consuming and requires a high degree of expertise for its implementation. With this in mind, it is needed to develop simplified J-estimation technique especially from the viewpoint of industrial requirements.

In this paper, updated simplified J-evaluation methods for the fatigue J-integral range and the creep J-integral are presented as a part of the flaw evaluation guideline for FBR components. The concepts of reference stress and elastic follow-up are utilized. The evaluation methods are then verified by comparing with the result of finite element analysis for a cracked cylinder.

CREEP-FATIGUE CRACK PROPAGATION LAW

In the flaw evaluation guideline, crack propagation law due to cyclic loading, $(da/dN)_f$, is given by,

$$(da/dN)_f = C_1 \cdot \Delta J_f^{m_1} \quad (1)$$

where ΔJ_f is the fatigue J-integral range [4] and m_1 is the material constant. C_1 is given as a function of the rise time (tension process time) so that the effect of the rise time on the crack propagation can be included [3]. This effect might be regarded as a part of creep crack propagation, however, it is practically difficult to separate its contribution.

Crack propagation law during hold time, $(da/dN)_c$, is given by

$$(da/dN)_c = \int_{\tau_0}^{\tau_1} \left[\frac{C_2}{\tilde{\varepsilon}_f} \cdot J'^{m_2} \right] dt \tag{2}$$

where τ_0 and τ_1 are times of the start and the end of holding, respectively, J' is the creep J-integral [5], C_2 and m_2 are the material constants, and $\tilde{\varepsilon}_f$ is the true fracture strain introduced to describe the effect of the applied stress level on the crack propagation rate [3]. Crack propagation rate at the same value of J' is accelerated with decreasing applied stress, and it can be explained by the reduction of ductility during cumulative holding. Since the crack propagation rate was found to be inversely proportional to the fracture strain under a constant strain rate [6], $\tilde{\varepsilon}_f$ is included in the crack propagation law as shown in Eq. (2). $\tilde{\varepsilon}_f$ is formulated as a function of the temperature and the cumulative holding time.

Creep-fatigue crack propagation rate, da/dN, is considered to be simply evaluated using a linear summation rule give by,

$$da/dN = (da/dN)_f + (da/dN)_c \tag{3}$$

It has been seen that the above equation is applicable to describe creep-fatigue crack propagation behavior at high temperature with an acceptable accuracy [7].

OUTLINE OF SIMPLIFIED J-EVALUATION METHODS

Various kinds of simplified methods have been developed for the evaluation of the fatigue J-integral range, ΔJ_f, and the creep J-integral, J', or its equivalent parameter [8-11]. All of them are derived from the simplified method to evaluate J-integral, J, under monotonic loading, and rely on the concept of the reference stress originally proposed by Ainsworth [8]. The reference stress method starts from the elastic J-integral obtained from the stress intensity factor. Inelastic response is then considered by multiplying the ratio of the elastic-plastic strain provided by the reference stress to the elastic strain. The consideration of inelastic response due to the existence of secondary stress is one of the key concerns for flaw evaluation at high temperature. Therefore, later works are especially devoted to the treatment of secondary stress based on the concept of elastic follow-up. Recently, JNC and CEA made a collaborative work on the applicability of simplified evaluation methods for fatigue and creep-fatigue crack propagation [10, 11].

The simplified J-estimation methods presented in this study is systematized including detailed provisions on the treatment of applied stress and reference stress and consistent evaluation procedure to realize reliable evaluation. The definite evaluation procedure will be given in the following sections.

MATERIAL CHARACTARIZATION AND ELASTIC FOLLOW-UP FACTORS

Cyclic Stress-Strain Relation

Cyclic stress-strain relation of the material is approximated by the following Ramberg-Osgood equation:

$$\frac{\Delta\varepsilon/2}{\varepsilon_0} = \frac{\Delta\sigma/2}{\sigma_0} + \kappa \left(\frac{\Delta\sigma/2}{\sigma_0} \right)^n, \quad \varepsilon_0 = \frac{\sigma_0}{E} \tag{4}$$

where $\Delta\sigma/2$ and $\Delta\varepsilon/2$ are half of the stress range and half of the strain range, respectively, σ_0 and ε_0 are material parameters for normalization of stress and strain, respectively, E is the Young's modulus, κ is the material constant, and n is the hardening exponent.

Creep Strain Relation

Creep strain relation of the material is approximated by the following Blackburn-type law:

$$\varepsilon_c = C_0 \{1 - \exp(-r_0 t)\} + C_1 \{1 - \exp(-r_1 t)\} + C_2 \{1 - \exp(-r_2 t)\} + \dot{\varepsilon}_m t \tag{5}$$

where ε_c is the creep strain, and the meaning of the other symbols is shown in Table 1.

Elastic Follow-Up Factors

Elastic follow-up factor was introduced in the design code for the prototype fast breeder reactor, Monju, for the purpose of assessing strain and stress under thermal stress [12]. For a circumferentially cracked cylinder, both the elastic follow-up factor related to plastic deformation, q_p, and the elastic follow-up factor related to creep deformation, q_c, are given by

$$q_p = q_c = 2.68 \exp\left[- 2.96 \left(\frac{a}{t} - 0.5 \right)^2 \right] \tag{6}$$

where a is the crack depth and t is the wall thickness. For a general cracked body, both q_p and q_c are conservatively considered to be equal to 4.

Table 1 Material Properties Used for Analysis

Cyclic Stress-Strain Relation	$\frac{\Delta\varepsilon/2}{\varepsilon_0} = \frac{\Delta\sigma/2}{\sigma_0} + \kappa \left(\frac{\Delta\sigma/2}{\sigma_0}\right)^n$ $E = 154$ GPa , $\nu = 0.3$ $\sigma_0 = 109$ MPa , $\varepsilon_0 = 0.000711$ $\kappa = 0.0274$, $n = 5.05$
Blackburn Type Creep Strain Relation	$\varepsilon_c = C_0\{1 - \exp(-r_0 t)\} + C_1\{1 - \exp(-r_1 t)\} + C_2\{1 - \exp(-r_2 t)\} + \dot{\varepsilon}_m t$ T : Temperature in [°C] , σ : Stress in [MPa] t : Time in [h] , t_r : Time to rapture in [h] ε_c : Creep strain in [mm/mm] , ε_m : Steady state creep strain rate $\log_{10} t_r = -28.951 + \frac{24488}{T + 273.15} + \frac{14425}{T + 273.15}\log_{10}\sigma - \frac{5390.6}{T + 273.15}(\log_{10}\sigma)^2$ $\dot{\varepsilon}_m = 13181 \exp\left(-\frac{79785}{8.31\,(T + 273.15)}\right) t_r^{-1.0865}$ $C_0 = 0.264\ \varepsilon_m^{0.370}$ $C_1 = 0.0824\ \varepsilon_m^{0.634} / r_1$ $C_2 = 0.0486\ \varepsilon_m^{0.666} / r_2$ $r_0 = 0.035$ $r_1 = 112.80\ t_r^{-0.921}$ $r_2 = 39.391\ t_r^{-1.05}$

EVALUATION METHOD FOR FATIGUE J-INTEGRAL RANGE

Elastic J-Integral Range

Elastic J-integral range, ΔJ_e, can be directly evaluated by the following equation:

$$\Delta J_e = \Delta K_I^2 / E' \tag{7}$$

where ΔK_I is the stress intensity factor range calculated by using the elastic applied stress obtained from elastic finite element analysis (or an equivalent method) for uncracked or cracked model. E' is equal to E at surface point or is equal to $E/(1-\nu^2)$ at internal point with the Poisson's ratio, ν.

Elastic Reference Stress and Strain Range

Elastic reference stress range, $\Delta\sigma^E_{ref}$, is the parameter provided by applied load range and the geometry of a cracked component and is generally given as

$$\Delta\sigma^E_{ref} = \frac{[\text{elastically calculated applied load range}]}{[\text{plastic collapse load}]} \times [\text{yield stress}] \tag{8}$$

Elastic reference strain range, $\Delta\varepsilon^E_{ref}$, is simply obtained by

$$\Delta\varepsilon^E_{ref} = \Delta\sigma^E_{ref} / E \tag{9}$$

Inelastic Reference Stress and Strain Range

Inelastic reference stress range, $\Delta\sigma^{EP}_{ref}$, and inelastic reference strain range, $\Delta\varepsilon^{EP}_{ref}$, are given as the solution of the following equations, which are schematically shown in Fig. 1.

$$q_p\left(\Delta\sigma^E_{ref} - \Delta\sigma^{EP}_{ref}\right) = 2\,\kappa\,\sigma_0\left(\frac{\Delta\sigma^{EP}_{ref}}{2\,\sigma_0}\right)^n \tag{10}$$

$$\Delta\varepsilon^{EP}_{ref} = \frac{\Delta\sigma^{EP}_{ref}}{E} + 2\,\kappa\,\frac{\sigma_0}{E}\left(\frac{\Delta\sigma^{EP}_{ref}}{2\,\sigma_0}\right)^n \tag{11}$$

Evaluation of Fatigue J-Integral Range

Fatigue J-integral range, ΔJ_f, can be evaluated by the following equation:

$$\Delta J_f = \frac{\Delta\sigma^{EP}_{ref} \cdot \Delta\varepsilon^{EP}_{ref}}{\Delta\sigma^E_{ref} \cdot \Delta\varepsilon^E_{ref}} \Delta J_e \tag{12}$$

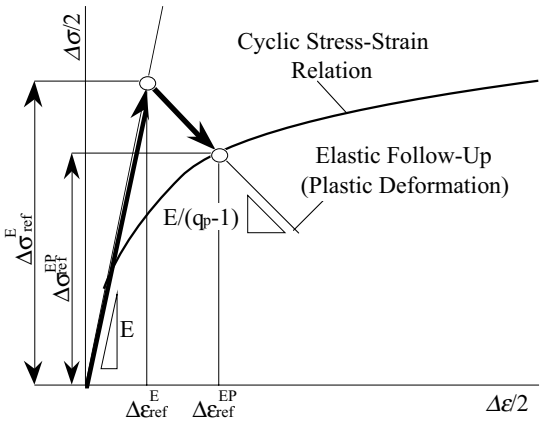

Figure 1 Evaluation Procedure of Inelastic Reference Stress and Strain Range

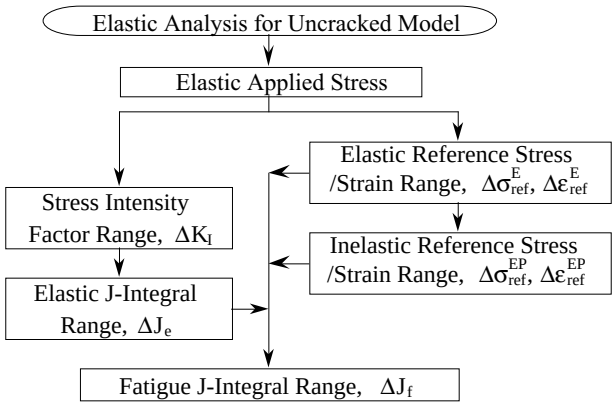

Figure 2 Evaluation Flow of Fatigue J-Integral Range

where $\Delta\sigma^{E}_{ref}$, $\Delta\varepsilon^{E}_{ref}$, $\Delta\sigma^{EP}_{ref}$, $\Delta\varepsilon^{EP}_{ref}$, and ΔJ_e are all calculated by the above-mentioned equations. Figure 2 shows the evaluation flow of ΔJ_f. It can be seen that once the elastic applied stress for uncracked model is obtained, ΔJ_f can be simply evaluated following the evaluation flow, with an appropriate stress intensity factor solution and an appropriate reference stress solution.

EVALUATION METHOD FOR CREEP J-INTEGRAL

Elastic J-Integral at the Beginning of Holding

Elastic J-integral at the beginning of holding, $J^{(0)}_e$, can be directly evaluated by the following equation:

$$J_e^{(0)} = \mathrm{Max}\left\{ K_I^{(max)2} / E',\ \left[\frac{\Delta K_I}{2}\right]^2 / E' \right\} \tag{13}$$

where $K_I^{(max)}$ and ΔK_I are the maximum stress intensity factor and the stress intensity factor range calculated by using the elastic applied stress obtained from elastic finite element analysis (or an equivalent method).

Elastic Reference Stress and Strain at the Beginning of Holding

Elastic reference stress at the beginning of holding, $\sigma^{E(0)}_{ref}$, is the parameter provided by applied load and the geometry of a cracked component and is generally given as

$$\sigma_{ref}^{E(0)} = \frac{[\text{elastically calculated applied load}]}{[\text{plastic collapse load}]} \times [\text{yield stress}] \tag{14}$$

Elastic reference strain at the beginning of holding, $\varepsilon^{E(0)}_{ref}$, is simply obtained by

$$\varepsilon_{ref}^{E(0)} = \frac{\sigma_{ref}^{E(0)}}{E} \tag{15}$$

Inelastic Reference Stress at the Beginning of Holding

Inelastic reference stress at the beginning of holding, $\sigma^{EP(0)}_{ref}$, and inelastic reference strain at the beginning of holding, $\varepsilon^{EP(0)}_{ref}$, are given as the solution of the following equations, which are schematically shown in Fig. 3.

$$q_p\left(\sigma_{ref}^{E(0)} - \sigma_{ref}^{EP(0)}\right) = \kappa\,\sigma_0\left(\frac{\sigma_{ref}^{EP(0)}}{\sigma_0}\right)^n \tag{16}$$

$$\varepsilon_{ref}^{EP(0)} = \frac{\sigma_{ref}^{EP(0)}}{E} + \kappa\,\frac{\sigma_0}{E}\left(\frac{\sigma_{ref}^{EP(0)}}{\sigma_0}\right)^n \tag{17}$$

Inelastic Reference Stress during Holding

Inelastic reference stress during holding, σ'^{EP}_{ref}, is given as the solution of the following equation, which is also schematically shown in Fig. 3.

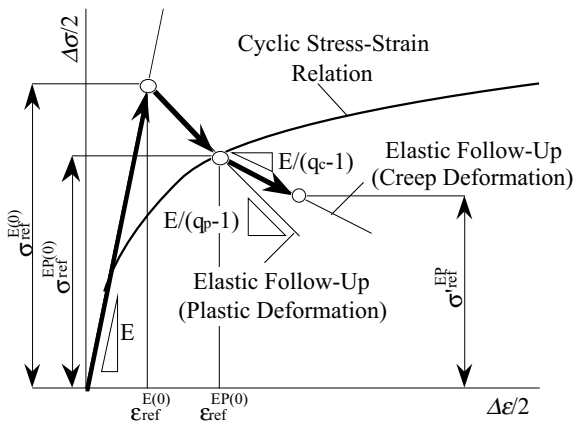

Figure 3 Evaluation Procedure of Inelastic Reference Stress and Strain

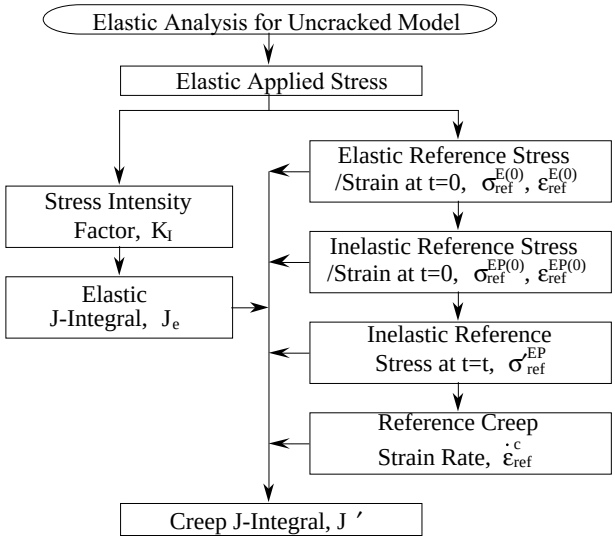

Figure 4 Evaluation Flow of Creep J-Integral

$$\sigma'^{EP}_{ref} = Max\left\{\sigma^{EP(0)}_{ref} + \int_0^{t_h} \dot{\sigma}^{c}_{ref}\, dt,\ P_{ref}\right\}, \quad \dot{\sigma}^{c}_{ref} = -\,E\,q_c\,\dot{\varepsilon}^{c}_{ref}, \quad \dot{\varepsilon}^{c}_{ref} = \frac{\partial \varepsilon_c\,(T,\ \sigma'^{EP}_{ref},\ \bar{t})}{\partial t} \tag{18}$$

where t_h is the holding time and $\bar{t}$ is the equivalent time. The effect of the relaxation of reference stress during holding is considered to be properly taken into account in Eq. (18). The lower limit of σ'^{EP}_{ref} is bounded by the maximum elastic primary reference stress, P_{ref}, so that the reference stress does not relax below the primary reference stress.

Evaluation of Creep J-Integral

Creep J-integral, J', can be finally evaluated by the following equation:

$$J' = \frac{\sigma'^{EP}_{ref} \cdot \dot{\varepsilon}^{c}_{ref}}{\sigma^{E(0)}_{ref} \cdot \varepsilon^{E(0)}_{ref}} J^{(0)}_e \tag{19}$$

where $\sigma^{E(0)}_{ref}$, $\varepsilon^{E(0)}_{ref}$, σ'^{EP}_{ref}, and $J^{(0)}_e$ are all calculated by the above-mentioned equations. $\dot{\varepsilon}^{c}_{ref}$ is the reference creep strain rate corresponding to σ'^{EP}_{ref}, and can be evaluated according to Blackburn-type law given by Eq. (5). Figure 4 shows the evaluation flow of J′, which is similar to that for ΔJ_f shown in Fig. 3.

VERIFICATION OF SIMPLIFIED J-EVALUATION METHODS

Object of Analysis

A cylinder with a semi-elliptical surface crack subjected to thermal loading as shown in Fig. 5 was used for the verification the simplified J-evaluation methods. The ratio of the inner radius to thickness is 10. The ratio of the crack depth to the thickness is fixed to 0.5, and the aspect ratio (crack depth / half crack length) is fixed to 0.5.

The thermal loading was caused by either linear temperature gradient with the temperature range, ΔT = 200 °C along thickness direction, or linear temperature gradient with ΔT = 600 °C along axial direction, as shown in Fig. 6. ΔT was determined so that the elastically applied stress for uncracked model was approximately equal to three times of the design stress intensity, S_m. For creep analysis, the linear temperature gradient was held for 10,000 hours.

The material properties used for the analysis were those of 316FR austenitic stainless steel base metal at 550 °C, as shown in Table 1.

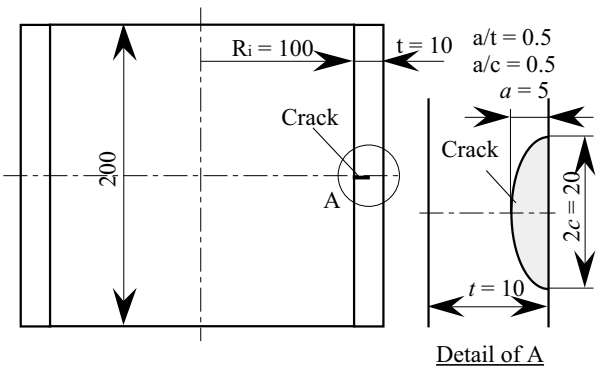

Figure 5 Object of Analysis

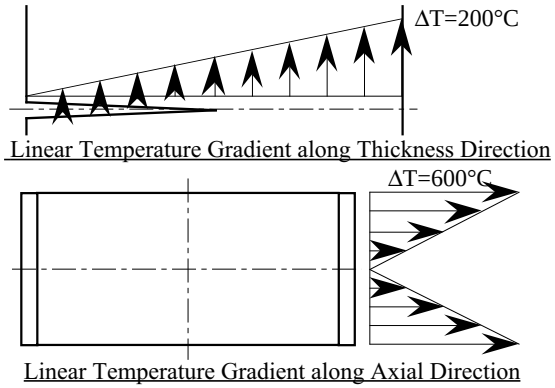

Figure 6 Thermal Loading Condition

Finite Element Analysis

The finite element analysis was conducted using the computer code, MARC. Twenty-noded brick elements were used for the three-dimensional analysis of a cylinder with a semi-elliptical surface crack subjected to thermal loading. Both ΔJ_f and J were calculated by the domain integration method, within four paths around the crack tip. Figure 7 shows an example of finite element mesh and J-integral paths. The path independence of ΔJ_f as well as J′ was separately confirmed, therefore, the average of path integrals was employed as the result of finite element analysis.

Application of Simplified J-Evaluation Methods

The applied stress used for the simplified J-evaluation was obtained from the elastic finite element analysis for uncracked model. The stress intensity factors for cracked cylinders were evaluated by using the solutions in Ref. [13]. The reference stress solution for a cylinder with a circumferential semi-elliptical surface crack was analytically provided as follows:

$$\sigma_{ref}^{E} = \left[\left(\frac{r\,(\sigma_m + \sigma_b)}{\sigma_0} \right)^2 + \frac{r\left(\sigma_b + \dfrac{\sigma_{bg}\, t}{2\, R_m}\right)}{3 \times \sigma_0} \right] \sigma_0 \qquad (20)$$

$$r = -0.877 \left(\frac{a}{t}\right)^2 - 0.421 \frac{a}{t} + 1\,, \quad x = -0.402 \left(\frac{a}{t}\right)^2 + 0.597 \frac{a}{t} + 0.544$$

where σ_m, σ_b, and σ_{bg} are the applied membrane stress, through-thickness bending stress, and global bending stress, respectively, σ_0 is the base stress in Eq. (4), R_m is the mean radius, t is the wall thickness, and a is the crack depth.

Comparison of Fatigue J-Integral Range

Figure 8 shows the change of ΔJ_f with increasing ΔT at the deepest point (eccentric angle from surface, $\theta = 90°$) and at the near-surface point ($\theta = 10°$) for linear temperature gradient along thickness direction, obtained from the simplified J-evaluation method and the finite element analysis. Similarly Figure 9 shows the change of ΔJ_f for linear temperature gradient along axial direction. ΔJ_f at the near-surface point evaluated by the simplified method is somewhat conservative than the result of the finite element analysis. However, ΔJ_f at the deepest point evaluated by the simplified method is in good agreement with the result of the finite element analysis for different types of temperature distribution.

Comparison of Creep J-Integral

Figure 10 shows the variation of J′ with the hold time at the deepest point and at the near-surface point obtained from the simplified J-evaluation method and the finite element analysis for linear temperature gradient along thickness direction. Similarly

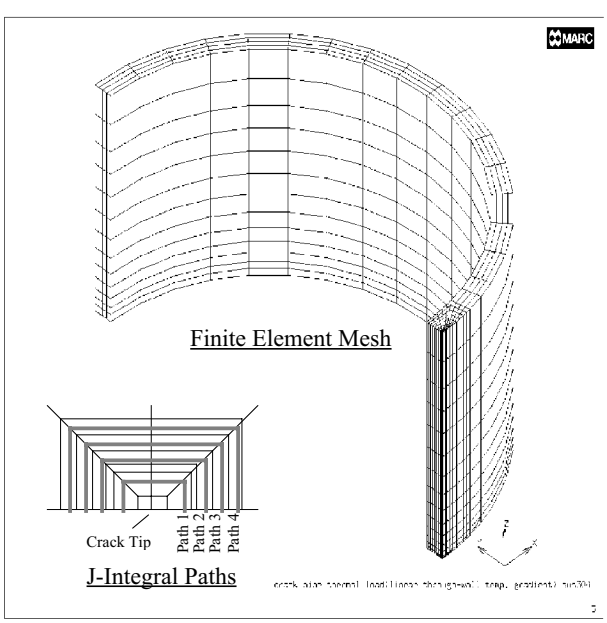

Figure 7 Example of Finite Element Mesh and J-Integral Paths

Figure 11 shows the variation of J′ for linear temperature gradient along axial direction. Rapid decrease of J′ is observed both in the simplified method and in the finite element analysis, which suggests the importance of considering stress relaxation during holding. J′ at the near-surface point evaluated by the simplified method is still larger than the result of the finite element analysis, while the simplified method and the finite element analysis give similar J′ at the deepest point.

CONCLUSIONS

In this study, updated simplified J-evaluation methods for the fatigue J-integral range and the creep J-integral were presented. The evaluation methods were based on the reference stress method combined with the concept of elastic follow-up. Although the proposed J-evaluation methods are provided on the assumption that the cyclic stress-strain relation and the creep strain relation can be described by Ramberg-Osgood equation and Blackburn-type law, respectively, the essential concept of the evaluation methods can be applied to arbitrary constitutive equations. The evaluation methods were incorporated in the revised

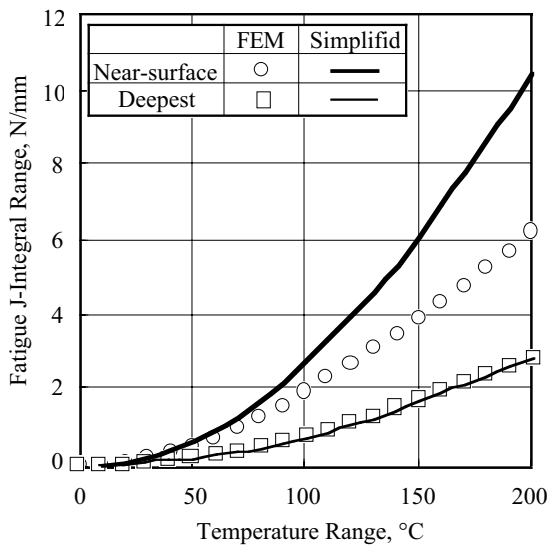

Figure 8 Comparison of Fatigue J-Integral Range for Linear Temperature Gradient along Thickness Direction

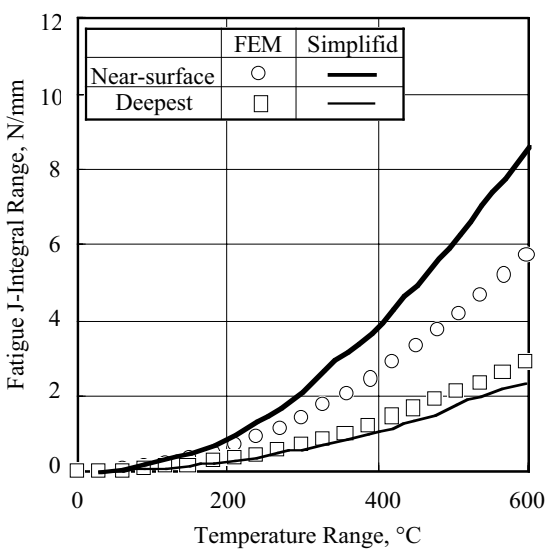

Figure 9 Comparison of Fatigue J-Integral Range for Linear Temperature Gradient along Axial Direction

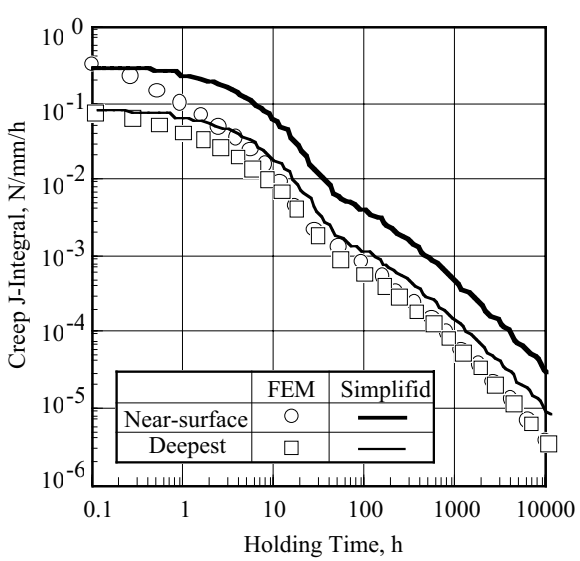

Figure 10 Comparison of Creep J-Integral for Linear Temperature Gradient along Thickness Direction

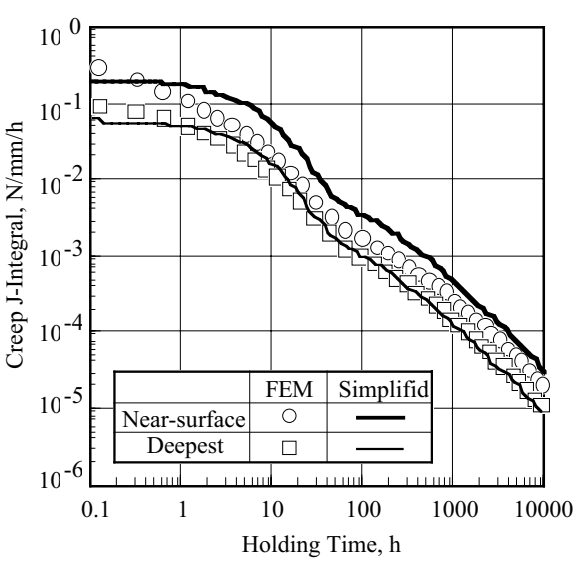

Figure 11 Comparison of Creep J-Integral for Linear Temperature Gradient along Axial Direction

guideline for the structural integrity assessment of high-temperature components of fast reactor plants, and can be used to describe the creep-fatigue crack propagation behavior. It was confirmed that the updated evaluation methods can provide accurate prediction, by comparing with the result of finite element analysis for a cracked cylinder.

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REFERENCES

1. Miura, N., Shimakawa, T., Nakayama, Y., and Takahashi, Y., "Simplified J-evaluation Method for Flaw Evaluation at High Temperature - Part I: Systematization of Evaluation Method," PVP-Vol. 410-1, Assessment Methodologies for Preventing Failure: Deterministic and Probabilistic Aspects and Weld Residual Stress, July, 2000, pp 111-118.
2. Shimakawa, T., Ogawa, H., Miura, N., Nakayama, Y., and Takahashi, Y., "Simplified J-evaluation Method for Flaw Evaluation at High Temperature - Part II: Verification of Evaluation Method," PVP-Vol. 410-1, Assessment Methodologies for Preventing Failure: Deterministic and Probabilistic Aspects and Weld Residual Stress, July 2000, pp 119-126.
3. Nakayama, Y., Miura, N., Takahashi, Y., Shimakawa, T., Date, S., and Toya, Y., "Development of Fatigue and Creep Crack Propagation Law for 316FR Stainless Steel in Consideration of FBR Operating Condition," PVP-Vol. 365, Fatigue, Fracture, and High Temperature Design Methods in Pressure Vessel and Piping, July 1998, pp 191-198.
4. Dowling, N. E., and Begley, J. A., "Fatigue Crack Growth During Gross Plasticity and the J-Integral," Mechanics of Crack Growth, ASTM STP 590, 1976, pp 82-103.
5. Landes, J. D., and Begley, J. A., "A Fracture Mechanics Approach to Creep Crack Growth," Mechanics of Crack Growth, ASTM STP 590, 1976, pp 128-148.
6. Nikbin, K. M., Smith, D. J., and Webster, G. A., "An Engineering Approach to the Prediction of Creep Crack Growth," Trans. ASME, Journal of Engineering Materials and Tecnology, Vol. 108, 1986, pp 186-191.
7. Miura, N., Nakayama, Y., and Takahashi, Y., "Development of Flaw Evaluation Guideline for FBR Components," Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology, Vol. V, paper G04/3, August 1999., pp 137-144.
8. Ainsworth, R. A., "Some Observations on Creep Crack Growth," International Journal of Fracture, Vol. 20, 1982, pp 147-159.
9. Iwasaki, R., Shimakawa, T., Nakamura, K., Takahashi, H., Uno, T., and Watashi, K., "Application of Simplified J-Estimation Methods to Surface Cracked Structures under Creep-Fatigue Loadings," Transactions of the 11th International Conference on Structural Mechanics in Reactor Technology, Vol. L, paper L10/2, August 1991, pp 217-222.
10. Wakai, T., Poussard, C., and Drubay, B., "A Comparison between Japanese and French A16 Defect Assessment Procedures for Fatigue Crack Growth," Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology, Vol. V, paper G03/1, August 1999, pp 79-86.
11. Poussard, C., Wakai, T., and Drubay, B., 1999, "A Comparison Between Japanese and French A16 Defect Assessment Procedures for Creep-Fatigue Crack Growth," Transactions of the 15th International Conference on Structural Mechanics in Reactor Technology, Vol. V, paper G03/3, August 1999, pp 95-102.
12. Iida, K., Asada, Y., Okabayashi, K., and Nagata, T., "Simplified Analysis and Design for Elevated Temperature Components of Monju," Nuclear Engineering and Design, Vol. 98, 1987, pp 305-317.
13. Chapuliot, S., "K_I Formula for Pipes with a Semi-Elliptical Longitudinal or Circumferential, Internal or External Surface Crack," CEA-R-5900, 2000.