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AN ESTIMATION METHOD OF THERMAL RATCHETTING OF CYLINDER SUBJECTED TO SHORT TRAVEL OF TEMPERATURE DISTRIBUTION

S. Kitade[1], M. Ueta[2], T. Kanaoka[3], H. Wada[4], T. Igari[1], K. Ogawa[5] and M. Jinbo[6]

[1]Mitsubishi Heavy Industries Ltd., Nagasaki, [2]The Japan Atomic Power Company, Tokyo, [3]Chugoku Electric Power Company, Hiroshima, [4]Mitsubishi Heavy Industries Ltd., Kobe, [5]Toshiba Corporation, Kawasaki, [6]Toshiba Corporation, Yokohama (Japan)

ABSTRACT

A new prediction equation for thermal ratchetting of a cylinder subjected to axially moving temperature distribution is proposed in this paper. This prediction equation considers the moving distance of temperature distribution. Predicted results correspond to analytical results by FEM and can conservatively estimate the experimental results.

1. INTRODUCTION

A prevention of progressive deformation by thermal ratchetting is one of the great concerns in the structural design of FBR components. Conventional ratchetting under the combination of primary stress and cyclic thermal stress has been studied by many researchers (Bree, 1967;Roche, 1982), and prediction methods are adopted by design codes.

A new type of ratchetting under thermal stress alone, on the other hand, has been paid attention. The representative case is the thermal ratchetting caused by the movement of hot sodium level during operation in the reactor vessel of FBR. As for this type of ratchetting, the experimental study confirming the ratchetting phenomena (Bell, 1982) and the proposal of the prediction equation for simple temperature distribution (Goodman, 1977;Wada et al., 1989) have been performed. In order to develop the practical prediction equation, the authors proposed an improved prediction equation which considered the effect of work hardening of material (Igari et al., 1991). But, these prediction equations assumed the long travel of temperature distribution.

In this paper, a new prediction equation considering the short travel of temperature distribution is proposed in order to develop more practical prediction equation applicable to the actual operating condition of FBR. The verification of proposed equation is performed by comparing predicted results with analytical ones by inelastic analyses and experiments.

2. PROPOSAL OF PREDICTION EQUATION

2.1 Conventional equation

The conventional prediction equation based on the elastic-perfectly-plastic material, which assumes the long travel of temperature distribution, is expressed as follows (Kaguchi et al., 1991).

$$|\Delta\varepsilon_R| = 2(|\sigma_{\theta,el}| - \bar{\sigma}_y)/E \qquad (1)$$

, where $\Delta\varepsilon_R$, $\sigma_{\theta,el}$ and E are the increment of ratchetting strain, the elastically-obtained-hoop-membrane stress and the Young's modulus, respectively. $\bar{\sigma}_y$ is the equivalent yield stress and is expressed as $\bar{\sigma}_y = \bar{\sigma}_y(\sigma_{\theta,el}, \sigma_{z,el})$, where $\sigma_{z,el}$ is an axial bending stress. The equation (1) is concretely expressed as follows.

$$|\Delta\varepsilon_R| = 2(|\sigma_{\theta,el}| - \bar{\sigma}_y)/E = Z\cdot\sigma_y/E \qquad (2)$$

, where σ_y is yield stress of material and the parameter Z is the ratchetting strain parameter defined in the previous work (Kaguchi et al., 1991). Ratchetting diagram by this equation is shown in Fig.1, where the horizontal axis is taken as the summation of hoop membrane stress and primary stress based on the concept of stress intensity of Tresca.

2.2 Ratchetting mechanism under short travel

The decrease of ratchetting strain increment under the short travel of temperature distribution was confirmed by inelastic analysis and experiments (Igari et al., 1989). Figure 2 shows the mechanism of the effect of moving distance. In the case of long travel of temperature distribution, the ratchetting deformation is shown as the solid line in this figure, and residual stress does not exist in the flat part of deformation at the center of traveling. Therefore, the ratchetting strain increment at this part is constant for every cycle.

On the other hands, in the case of short travel, the deformation at the center of traveling becomes small due to the constraint by the regions ab and cd which are not subjected to the traveling. As a result, the residual stress occurs in opposite direction to the progress of ratchetting deformation, and the ratchetting strain increment at the second cycle becomes smaller than at the first cycle by the effect of this residual stress. After a number of cycles, the ratchetting strain increment becomes smaller, and the residual stress becomes larger. However, when the residual stresses in the regions ab and cd, which are proportional to the stress in the region bc, become large and reach the yield stress, the effect of the constraint of deformation is thought to be saturated and the ratchetting strain increment is thought to become constant.

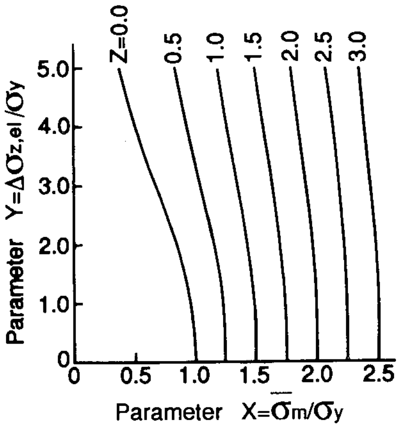
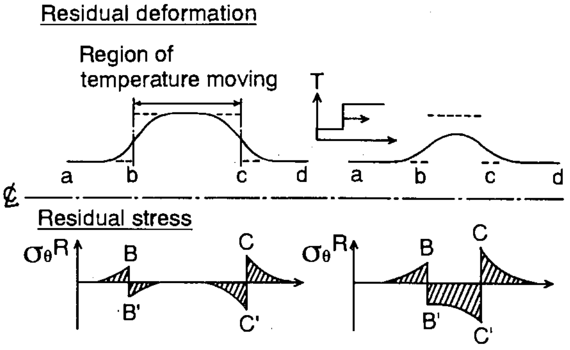


Fig.1 Ratchetting diagram



(a) Long travel (b) Short travel

Fig.2 Mechanism of the effect of moving distance

2.3 Prediction equation

It is necessary to predict the change of residual stress in order to predict the ratchetting strain increment of short travel. In this study, a prediction equation is proposed by assuming the short travel of hot-spot-shaped temperature distribution.

Figure 3 shows the hoop-membrane stress-strain behavior assuming the elastic-perfectly-plastic material in the case of movement of hot-spot-shaped temperature distribution. In the case of long travel, the ratchetting strain increment is expressed as the eq.(3) by assuming the following condition.

Assumption

$\varepsilon=0$ and $\sigma=0$ at point A

$\sigma=0$ at point E

ε(process AB)$=\varepsilon$(process DE)

ε(process BC)$=\varepsilon$(process CD)$=\alpha\Delta T$

$$\begin{array}{llll} |\Delta\varepsilon_R| & = 2\sigma_y/E & \text{----------------} & 2\sigma_y<E\alpha\Delta T \\ & = 2(E\alpha\Delta T-\sigma_y)/E & & \\ & = 2(\sigma_{\theta,el}-\sigma_y)/E & \text{---------} & \sigma_y<E\alpha\Delta T\le 2\sigma_y \end{array} \tag{3}$$

, where α and ΔT are the thermal expansion coefficient and the temperature difference in the hot-spot-shaped temperature distribution. Under the condition of "$\sigma_y<E\alpha\Delta T\le 2\sigma_y$", the ratchetting strain increment for hot-spot shaped temperature distribution is equal to that for step change temperature distribution shown in the eq.(1) by replacing σ_y by $\bar{\sigma}_y$.

In the case of short travel, the prediction equation for the ratchetting strain increment can be obtained as follows (Kitade et al. 1993). By assuming that the total increment of the reaction force of cylinder based on the elastic theory of cylindical shell when supposing that the radius of cylinder at the passing point of hot-spot decreases, is equal to the increment of the reaction force caused by the movement of temperature distribution with the small length "dl", that is to say, $\sigma_0 dl$ (where σ_0 is the stress increment in the process of BD in Fig.3), the following equations can be obtained.

$$|\Delta\varepsilon_R|=(\varphi+1)\ \gamma_0^{N-1}(|\sigma_{\theta,el}|-\sigma_y)/E \tag{4}$$

$$\varphi=1-1/2(1+\cos\ \beta l+\sin\ \beta l)\ \bullet\ e^{-\beta l} \tag{5}$$

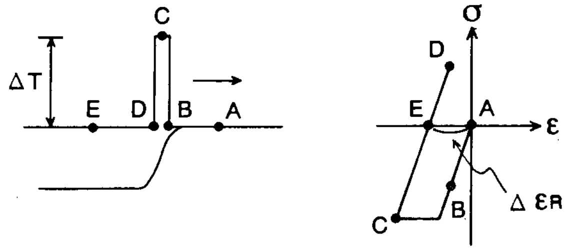


Fig.3 Hoop-membrane stress-strain behavior in the case of movement of hot-spot-shaped temperature distribution

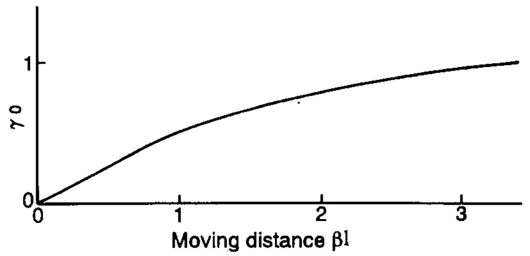


Fig.4 Relationship between γ_0 and βl

, where N is the number of cycle, and γ_0 is a constant depending on the moving distance of temperature distribution as shown in Fig.4. As for the case in which the stresses at boundaries of traveling reach the yield stress, on the other hand, the following prediction equation is proposed by assuming that the ratchetting strain increment becomes constant after either stress of start point or end point of traveling reaches the yield stress.

$$|\Delta\varepsilon_R| = (1+\varphi)\bullet\gamma_0^{N_s-1}(|\sigma_{\theta,el}|-\sigma_y)/E \qquad (6)$$

, where Ns denotes the number of cycle when the plastic yielding occurs at either boundary of traveling. Figure 5 shows the boundary between the ratchetting region and the shakedown region. The accumulated ratchetting strain in the shakedown region can be obtained by the eq.(4) and is expressed as follows.

$$\varepsilon_R = (1-\gamma_0^N)/(1-\gamma_0)\bullet(\varphi+1)(|\sigma_{\theta,el}|-\sigma_y)/E \qquad (7)$$

3. COMPARISON BETWEEN PREDICTION AND FEM ANALYSIS

The propriety of proposed equations is verified by comparing the predicted results with those by FEM analysis. Elastic-plastic analyses assuming the elastic-perfectly-plastic material for the step-change-shaped temperature distribution are performed under the condition of several kinds of moving distance (βl=0.5~3) and several stress level ($\sigma_{\theta,el}/\sigma_y$=1.0~1.5).

Figure 6 shows the comparison of accumulated ratchetting strains at the final cycle (about 50th cycle) obtained by the conventional and the proposed equation together with those by FEM. Predicted ratchetting strains by the conventional equation expressed as the eq.(1) by replacing σ_y by σ_y are much conservative when compared with analytical ones. On the other hand, predicted ratchetting strains by the proposed equations expressed as the eqs.(4) and (6), which consider the effect of moving distance, coincide well with analytical ones.

4. COMPARISON BETWEEN PREDICTION AND EXPERIMENT

A series of experiments are performed by using the thin-walled cylinder

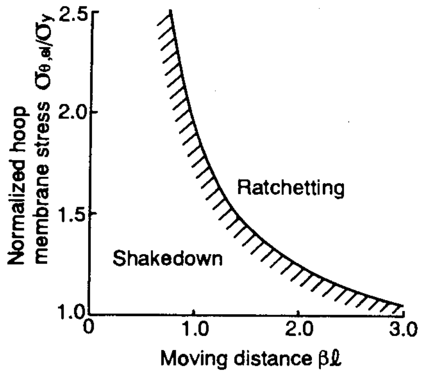
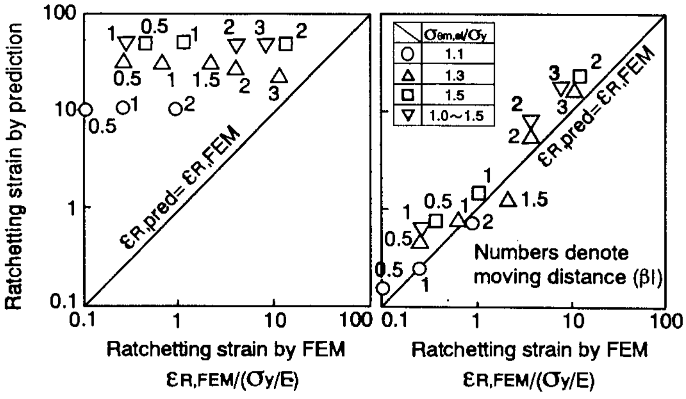


Fig.5 Ratchetting region predicted by proposed equation



(a) Conventional method (b) Proposed method

Fig.6 Comparison of predicted ratchetting strains with those by FEM with a mean radius of 76.5mm and thickness of 2mm of Type 316 stainless steel and 316FR stainless steel (with low carbon and medium nitrogen) in order to verify the propriety of proposed equations. Testing procedure and apparatus are the same as previous works (Ogawa et al., 1991).

Table 1 shows testing conditions. In this study, the tests with two types of temperature hold in addition to the test without temperature hold are also performed in order to examine the creep effect on ratchetting behavior. One type is a uniform hold at 650°C after unloading of temperature distribution at every cycle and another type is a hold with temperature distribution.

Figure 7 shows the comparison of accumulated ratchetting strains at final cycle obtained by the prediction equation and those by experiment, where the prediction equation considers both effect of work hardening of material and moving distance. As shown in this figure, the proposed equation can conservatively estimate the accumulated ratchetting strains in the both cases with and without temperature hold.

5. PROPOSAL OF A DESIGN PROCEDURE

When applying the proposed prediction equations expressed as the eqs.(4) and (6) to the actual design of component, a few problems must be clarified as follows.

(1) Clarification of the applicable region of prediction equations
(2) Coupling of the effect of work hardening and short travel
(3) Clarification of the creep effect

As for the problem (1), the applicable region corresponds to shakedown region shown in Fig.5 under the condition of "$\sigma_{\theta,el}/\sigma_y \leq 2$". The reasons for adopting this region are that the accumulated ratchetting strain in the ratchetting region shown in Fig.5 becomes greater than the limit strain when the number of cycles becomes large, and that the eqs.(4) and (6) can be meaningful under the condition of "$\sigma_{\theta,el}/\sigma_y \leq 2$" as shown in the eq.(3).

As for the problem (2), it is thought to be better for simplicity that the prediction equations considering short travel are applied to the shakedown region only as mentioned above and the prediction equation considering work hardening of material is applied to the ratchetting region only shown in Fig.5.

As for the problem (3), the increase of ratchetting strain due to creep

Table 1 Testing conditions

T_{max} (℃)	Material	Type of hold	Mov. direc.	Hold time (hr)	$\frac{\sigma_{\theta,el}}{\sigma_y}$	βl
650	SUS316	uniform temperature	Cold-front	10	1.2	5.0
				0	1.2	5.0
				10	1.2	2.0
				0	1.2	2.0
	316FR	with temperature distribution	Hot-front	10	1.4	2.0
				0	1.4	2.0
				0	1.4	6.0
		——	Cold-front	0	1.4	2.0
					1.4	1.0
					1.8	2.0
					1.8	1.0

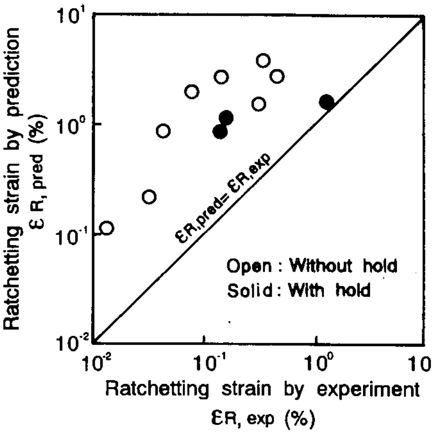


Fig.7 Comparison of predicted ratchetting strains and experimental ones

is found in experiment, but the proposed equations conservatively estimate the ratchetting strain under creep condition as shown in Fig.7. Therefore, it may be unnecessary to modify the proposed prediction equations in order to consider the creep effect.

6. CONCLUSION

A new prediction equation considering short travel of temperature distribution was proposed. Predicted results based on this equation corresponded to analytical results by FEM and could conservatively estimate the experimental results with and without temperature hold.

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