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Inelastic Ratcheting Constitutive Models for A GEN-IV Reactor Structural Design Subjected to Elevated Temperature Operations

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1. Introduction

In this paper, an investigation of various inelastic ratcheting constitutive models for a GEN-IV reactor structural design subjected to elevated temperature operations is carried out. For a inelastic analysis of a ratcheting strain, various nonlinear kinematic hardening models such as the Prager Model, Armstrong and Frederick Model, Chaboche Model[1], Chaboche Model with a Threshold, and Ohno and Wang Model[2] are investigated. To carry out the simulations for all the models, the computer program PARA-ID code is developed. This code implements the radial return algorithm to simulate the cyclic behavior for each model with extracted plastic modulus.

2. Constitutive Models for Ratcheting Strain

When the state of a stress is over the elastic limit and the loading continues, a material hardening behavior can occur with one of two types or both. One is a kinematic hardening accounting for the yield surface translation in a deviatoric stress space. The other one is an isotropic hardening accounting for an expansion of the yield surface without its translation. However, the most important one of these for a ratcheting simulation is the kinematic hardening rule. This rule will be investigated for various inelastic constitutive models.

2.1 Prager Model

Prager (1956) has proposed the simplest kinematic hardening rule to simulate the plastic behavior of materials as follows;

$$\dot{\alpha}_{ij} = C\dot{\varepsilon}_{ij}^{p} \tag{1}$$

In this model, the yield surface moves linearly with the plastic strain in the trace of the backstress and the hysteresis loop shows a bilinear stress-strain curve. Therefore, this model can not represent the nonlinear part of the hysteresis loop. Furthermore, this model only produces a closed hysteresis loop for a prescribed uniaxial stress cycle with a mean stress, thus it can not simulate the ratcheting behavior properly.

2.2 Armstrong and Frederick Model

To improve the linear kinematic hardening model, Armstrong and Frederick have proposed a nonlinear kinematic hardening model, which can describe the nonlinear parts of the hysteresis loop with a memory effect of the strain path. The kinematic hardening rule in this model is represented with the evolution of the deviatoric backstress as follows;

$$\dot{\alpha}_{ij} = \frac{2}{3}C\dot{\varepsilon}_{ij}^{p} - \gamma\alpha_{ij}\dot{p} \tag{2}$$

This model is the most well-known nonlinear kinematic hardening model but it can not still describe the nonlinear portion of the hystersis loop in detail.

2.3 Chaboche 3-Decomposed Model

To improve the deficiency of the Armstrong and Frederick model for a ratcheting simulation, Chaboche and his co-workers proposed a 'decomposed' nonlinear kinematic hardening rule as follows;

$$\dot{\alpha}_{ij} = \sum_{k=1}^{n}(\dot{\alpha}_{ij})_k = \sum_{k=1}^{n}\left(\frac{2}{3}C_k\dot{\varepsilon}_{ij}^{p} - \gamma_k(\alpha_{ij})_k\dot{p}\right) \tag{3}$$

As expressed in Eq.(3), the Chaboche kinematic hardening model is basically a superposition of several Armstrong and Frederick hardening rules. However, this model is known to result in some lower stiffness characteristics just after a yield.

2.4 Chaboche Model with Threshold Stress

To overcome the deficiencies of the Chaboche 3-decomposd model, Chaboche proposed a 4-decomposed nonlinear hardening rule with a concept of a 'threshold' as follows (Chaboche, 1991) ;

$$\dot{\alpha}_{ij} = \sum_{k=1}^{4}(\dot{\alpha}_{ij})_k = \sum_{k=1}^{4}\left(\frac{2}{3}C_k\dot{\varepsilon}_{ij}^{p} - \gamma_k(\alpha_{ij})_k\left\langle 1 - \frac{A_k}{f(a_k)}\right\rangle\dot{p}\right) \tag{4}$$

2.5 Ohno and Wang Model

Ohno and Wang have proposed the multi-decomposed nonlinear kinematic hardening rules based on dividing the hardening curve into many linear segments like the multilinear hardening model.

$$\dot{\alpha}_{ij} = \sum_{k=1}^{n}(\dot{\alpha}_{ij})_k = \sum_{k=1}^{n}\left\{\frac{2}{3}C_k\dot{\varepsilon}_{ij}^{p} - \gamma_k(\alpha_{ij})_k\left\langle\dot{\varepsilon}_{ij}^{p}\bullet\frac{(\alpha_{ij})_k}{f(a_k)}\right\rangle\left(\frac{f(a_k)}{C_i/\gamma_i}\right)^{m_i}\right\} \tag{5}$$

In the above equation, a slight nonlinearity is expressed with the multiplier with a power of m_i and it has a role of preventing the stress-controlled hysteresis loop from being a closed loop and causing a ratcheting behavior.

2.6 Comparison Results

2.6.1 Stress-Controlled Cyclic Behavior

The stress-controlled cyclic behavior calculated by the constitutive models such as the Armstrong and Frederick model, the Chaboche 3-decomposed model, the Chaboche 4-decomposed model, and the Ohno and Wang model are compared with the experimental data published in a reference paper (Bari, 2000). As shown in Fig. 1(a), the hysteresis loop by a simple Armstron and Frederick model is very different from that of an experiment. On the other hand, the Chaboche 3-decomposed model predicts the cyclic behavior very well when compared to the experimental result but it still shows a lower stiffness during the initial nonlinear part. The Chaboche 4-decomposed model overcomes the low stiffness problem occurring in the 3-decomposed Chaboche model as shown in Fig. 1(c). The hysteresis loop obtained by the Ohno and Wang model (Fig. 1(d)) shows a very good agreement with that of the experiment.

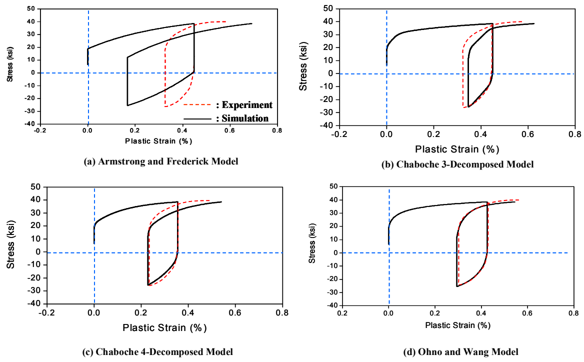

Fig. 1 Comparison of Stress-Controlled Cyclic Behavior

2.6.2 Strain-Controlled Cyclic Behavior

Fig. 2 shows a comparison of the strain-controlled hysteresis loops obtained by each model. As shown in the figure, the Armstrong and Frederick model can not predict the nonlinear part accurately. The Chaboche models can describe the nonlinear behavior well but it still shows some discrepancies when compared to an experimental result in the nonlinear portion. However, the hysteresis loop by the Ohno and Wang model shows a very good agreement with that of the experiment in the overall loop locus.

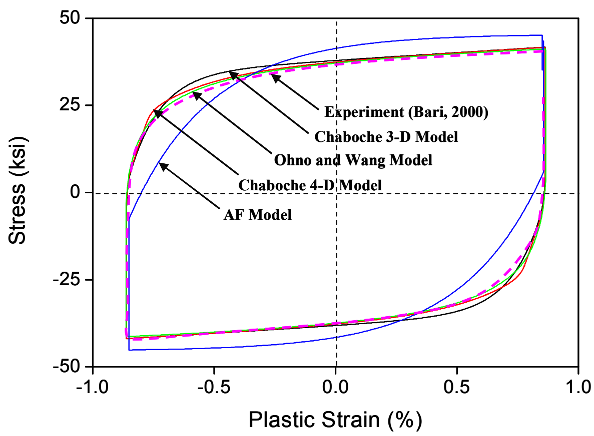

Fig. 2 Comparison of Strain-Controlled Cyclic Behavior

2.6.3 Ratcheting Behavior

To compare the ratcheting strains obtained by each constitutive model, the maximum peak strain in each cycle is plotted as a function of the number of cycles. Fig. 3 shows the comparison of the ratcheting increments for each model. As shown in the figure, the Armstrong and Frederick model shows a significant over-predicting of a ratcheting. The Chaboche 3-decmposed model shows a slightly different ratcheting accumulation during the initial cycles when compared to that of the Chaboche 4-decomposed model but almost the same total accumulated strain after a couple of cycles. The overall simulation by these models still deviates from the experiments with an over-prediction. Among the constitutive models investigated in this study, it is revealed that the Ohno and Wang model provides the best uniaxial ratcheting prediction.

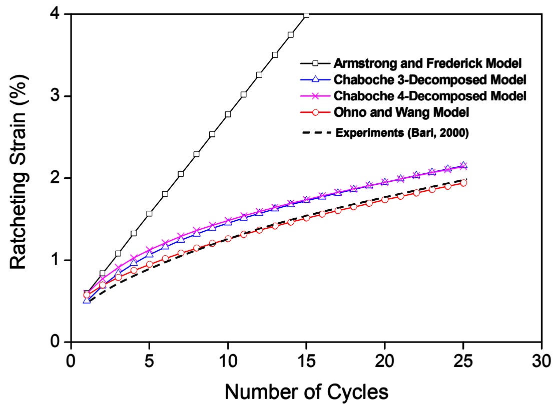

Fig. 3 Comparison of Ratcheting Strain Accumulation

3. Conclusions

In this paper, various inelastic ratcheting constitutive models are investigated and compared with each other to be used for the GEN-IV elevated temperature structural design. From this study, it is found that the inelastic constitutive model has to be selected carefully for an inelastic ratcheting analysis because even a small over- prediction of a steady accumulating ratcheting rate can result in a significant over-estimation after a whole life cycle. At least, the Chaboche model is recommended for the ratcheting analysis.

ACKNOWLEDGMENTS

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