On The Determination of the Inelastic Material Parameters for the NONSTA Code

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1. Introduction

The Liquid Metal Reactor (LMR) structures are subjected to a high temperature operating condition above 500°C[1] and thus the inelastic behavior and creep-fatigue damage are the principal concerns to be dealt with for its structural integrity. The high temperature inelastic analysis accounting for both the time independent plasticity and time dependent creep behaviors for a reliable structural safety assessment is necessary. Chaboche's viscoplasticity constitutive model[2] is one of the promising models. In this study, Chaboche's unified viscoplasticity model was implemented into a general purpose finite element code ABAQUS[3] as a subroutine NONSTA[4-5]. Since the inelastic behavior of a high temperature structure is highly nonlinear, the selection of the material parameters of the inelastic constitutive equations influences the analysis results in a large way. The effects of material parameters in the NONSTA code have already been analyzed by Jeon[6] and Kim[7]. In this study, the determination methodology of the inelastic material parameters for the NONSTA code is presented and the parameter values for 15% cold worked type 316L stainless steel[8] have been obtained.

2. Methods and Results

The constitutive equations implemented into the NONSTA code are explained briefly. The stress-strain relationship can be defined as

$$\dot{\sigma} = \mathrm{E}(\dot{\varepsilon} - \dot{\varepsilon}_p) = \mathrm{E}\left\{\dot{\varepsilon} - \frac{3}{2}\left\langle \frac{J(\mathbf{s}-\boldsymbol{X})-(R+\kappa)}{K}\right\rangle^n \frac{\mathbf{s}-\boldsymbol{X}}{J(\mathbf{s}-\boldsymbol{X})}\right\} \quad (1)$$

The viscoplastic strain rate($\dot{\varepsilon}_p$) and the accumulated plastic strain rate($\dot{p}$) are

$$\dot{\varepsilon}_p = \dot{p}\mathbf{n}, \quad \dot{p} = \left\langle \frac{J(\mathbf{s}-\boldsymbol{X})-(R+\kappa)}{K}\right\rangle^n, \quad \mathbf{n} = \frac{3}{2}\frac{\mathbf{s}-\boldsymbol{X}}{J(\mathbf{s}-\boldsymbol{X})} \quad (2)$$

The kinematic hardening and isotropic hardening evolutions are defined as

$$\dot{X} = \frac{2}{3}C\dot{\varepsilon}_p - \gamma X\dot{p} = \left(\frac{2}{3}C\mathbf{n} - \gamma X\right)\dot{p} \quad (3)$$

$$\dot{R} = b(Q-R)\dot{p} \quad (4)$$

where C, γ, Q, b, and κ are the material parameters. X is the back stress, R is the drag stress (change in the size of elastic domain), p is the accumulated plastic strain, and function <x> is defined as: <x>=x if x ≥ o, <x>=0 if x < 0.

2.1 Kinematic Hardening Parameters

The kinematic hardening variables C and γ in Equation (3) are determined using a cyclic curve. The kinematic hardening term represents the tensile hardening behavior according to Masing's rule as well as the movement of a center of the yield surface. The cyclic curve is fitted into a single stress-strain relationship and its differentiation with respect to the plastic strain range yields

$$\frac{d\sigma_t}{d\frac{\Delta\varepsilon_p}{2}} = \bar{n}\bar{K}\left(\frac{\Delta\varepsilon_p}{2}\right)^{\bar{n}-1} \quad (5)$$

The tensile peak stress is expressed as

$$\sigma_t = \frac{c}{\gamma}\tan h\left(\frac{\gamma\Delta\varepsilon_p}{2}\right) + Q + \kappa + K\left(\dot{\varepsilon}_p\right)^{\frac{1}{n}} \quad (6)$$

The differentiation of Equation (6) with respect to the plastic strain range yields

$$\frac{\partial\sigma_t}{d\frac{\Delta\varepsilon_p}{2}} = \frac{c}{\gamma}\cdot\gamma\cdot\sec h^2\left(\frac{\gamma\Delta\varepsilon_p}{2}\right) \quad (7)$$

Now we can obtain values of C/γ and γ from Equation (5) and Equation (7) by utilizing the least square technique. Excel software was used for numerical procedure and the optimal values of C and γ obtained from Figure 1 are 41440MPa and 224, respectively.

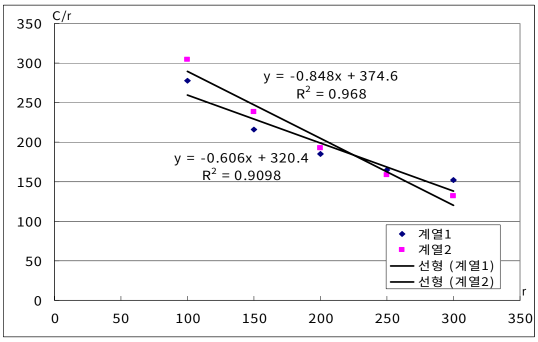

Figure 1. Determination of C and γ

It is worth noticing the above procedure is not affected by other material parameters.

2.2 Viscoplastic Stress Parameters

The essential difference of a unified viscoplasticity model from other plasticity models is the introduction of the viscoplastic stress term σ_v which is the last term in Equation (6). The material parameters K and n are to be determined from a long term creep test or stress relaxation test data. Unfortunately, it is not easy to secure this data and thus a new procedure by making use of two tensile data with different strain rates is presented. Figure 2 shows the two tensile curves of which the strain rates are $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ respectively. The stress difference $\Delta\sigma_a$ is expressed by

$$\Delta\sigma_a = K\left[\left(\dot{\varepsilon}^p_{a_2}\right)^{\frac{1}{n}} - \left(\dot{\varepsilon}^p_{a_1}\right)^{\frac{1}{n}}\right] \quad (8)$$

The total strain is expressed by summation of elastic strain and plastic strain as

$$\varepsilon = \varepsilon^{el} + \varepsilon^{p} = \frac{\sigma}{E} + \left(\frac{\sigma}{K^*}\right)^{\frac{1}{n^*}} \quad (9)$$

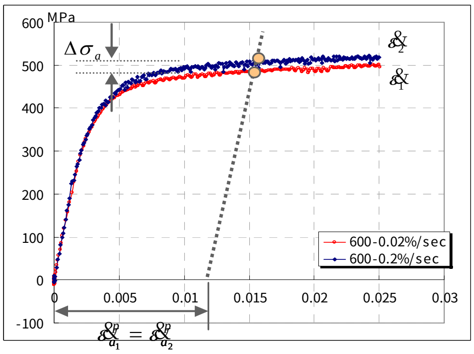

Figure 2. Tensile curves with different strain rates

The plastic strain and the plastic strain rate can be obtained by a curve fitting and then the least square method can be used to find the optimal values of K and n. For a cold worked SS316L, K and n are 176MPa and 8.13, respectively.

2.3 Cyclic Hardening Parameters

The cyclic hardening parameters b and Q in Equation (4) shall be obtained from cyclic hardening (or softening) data as shown in Figure 3. In this process, the effects of the previously obtained kinematic hardening variables and the viscoplastic stress terms need to be included and the parameter κ needs to be adjusted properly with considerable caution. Optimal values of b, Q, and κ are 0.97, -52MPa, and 279MPa, respectively. It is noteworthy that the value of Q is negative so that it can express the cyclic softening behavior of the cold worked SS316L properly.

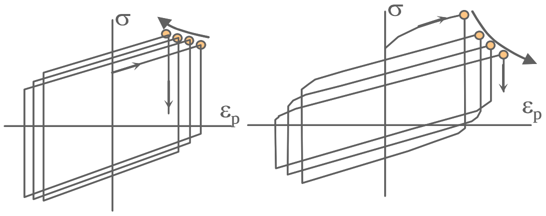

Figure 3. Cyclic hardening and cyclic softening

2.4 Validation

With the determined parameter values, the calculated results were compared to those of the test results. Figure 4 shows the comparison of the test result with the calculated results using several sets of parameter values. It is confirmed that the presented method(vp-case6a) to determine the optimal material parameters yields satisfactory results. It is also confirmed that this gave a good representation of the typical cyclic softening behavior.

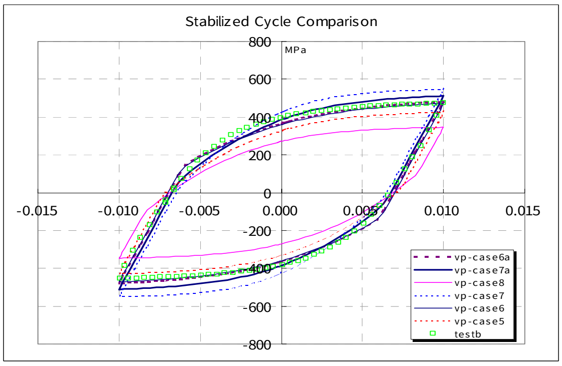

Figure 4. Comparison of analysis results with test result

3. Conclusion

The method to determine the inelastic material parameters for the NONSTA code is presented and the parameters for a cold worked SS316L are obtained. The inelastic analysis by using the obtained values showed a good agreement with the test result.

ACKNOWLEDGMENT

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