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Computation of material parameters of Chaboche kinematic hardening model using grey wolf optimization and uniaxial ratcheting prediction of SS316 Stainless Steel

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Abstract: *This paper deals with the computation of hardening parameters using the Grey wolf optimization (GWO) approach with finite element (FE) simulation to study the uniaxial ratcheting behavior of SS316 stainless steel. Chaboche's kinematic hardening model is used to predict this kind of cyclic plastic phenomenon of the material. Ratcheting strain occurs even after the saturation of the material. The parameters obtained from a strain-controlled saturated hysteresis loop are used in the material model. The material model is a plugged infinite element commercial package, ABAQUS, for simulation of ratcheting behavior. The finite element simulation is based on the Von-Mises yield function, flow rule, kinematic hardening rule, and yield surface consistency condition. The proposed optimization technique, GWO, is used for material parameters optimization of SS 316 steel. The simulation results are compared to the one obtained using manually determined parameters. The simulation results confirm the potentiality and efficacy of the proposed KHA method.*

Keywords*: hardening parameters, Grey wolf optimization, Finite element, ratcheting, Von-Mises yield function.*

I. Introduction

In structural components design, mechanical behavior modeling of material is very important to estimate the fatigue life. The mechanical behaviors of materials are modeled initially by the linear Prager [1] model. Subsequently, the advanced plasticity models are proposed by Armstrong and Frederick [2], Chaboche [3], Ohno, and Wang [4] and others.

Chaboche model is the segmentation of Armstrong and Frederick's rule to get segment-wise better results. This decomposition better describes the three critical segments of the loading/unloading branch of the saturated hysteresis loop, i.e., initial part with high modulus, transition knee zone, and linear part at high strain range.

Ratcheting is one of the important cyclic plastic phenomenons of the material. In ratcheting, the strain accumulation occurs in loading direction when the material is subjected to stress-controlled cyclic loading with non-zero mean stress. For developing the constitutive models for ratcheting, a lot of efforts are found from the contributors like Burlet&Cailletaud [5], Chaboche et al. [6,7], Guionnet [8], Ohno and Wang [9], Hassan and Kyriakides [10,11], Delobelle et al. [12], McDowell [13], Jiang and Sehitoglu [14], Ohno [15] and others. Above all the Chaboche's model provides a better result for ratcheting simulation. Each model has a large number of material parameters, is determined from different experimental responses. Manual parameter determination for a model is tedious and error-prone. Therefore the optimization technique can be used to automate the optimization of model parameters.

In reference [16-19], genetic algorithm (GA) optimization techniques have been adopted by many researchers for material parameters optimization.

This present work aims to develop a simple and efficient optimization technique to overcome the drawbacks above. Recently, Gandomi [20] proposed a new nature-inspired, population-based meta-heuristic optimization technique, namely krill herd algorithm (KHA), for solving complex numerical problems. The KHA algorithm has excellent exploration and exploitation capabilities, which avoid local optimality and quickly reach the optimal solution.

II. Experimental procedure

A. Uniaxial ratcheting tests

The ratcheting phenomenon is one of the low cycle fatigue responses. The cylindrical fatigue specimen (Figure-1) is used for testing, and the test has been conducted under load-controlled mode. The loading history of the experiment is shown in Figure-2. The tests have been conducted in the universal testing machine(Instron UTM)(Figure-3) with 8810 controllers and a data acquisition system. The ratcheting experiments are conducted at various combinations of mean stresses and stress amplitudes. Those are m40a310, m60a310, m80a310, m80a270 and m80a350 respectively. The ratcheting load m40a310 implies that mean stress is 40MPa, and stress amplitude is 310 MPa. Figure-4 shows the uniaxial ratcheting response for the ratcheting load m80a350. The ratcheting strain variation with cycles under constant mean stress but varying amplitudes of stress is shown in Figure-5(a), whereas Figure-5(b) shows the variation of ratcheting strain with cycles under varying degrees mean stresses with constant stress amplitude.

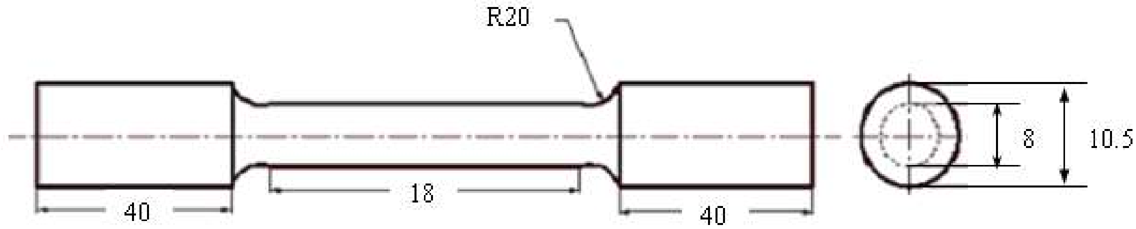


Fig 1: Uniaxial Fatigue Specimen

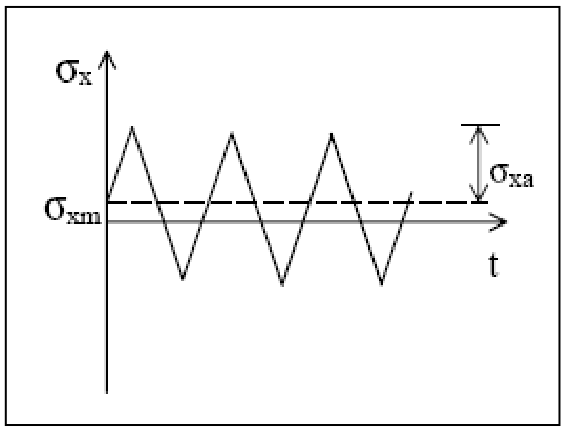


Fig-2: Loading histories; uniaxial stress cycles.

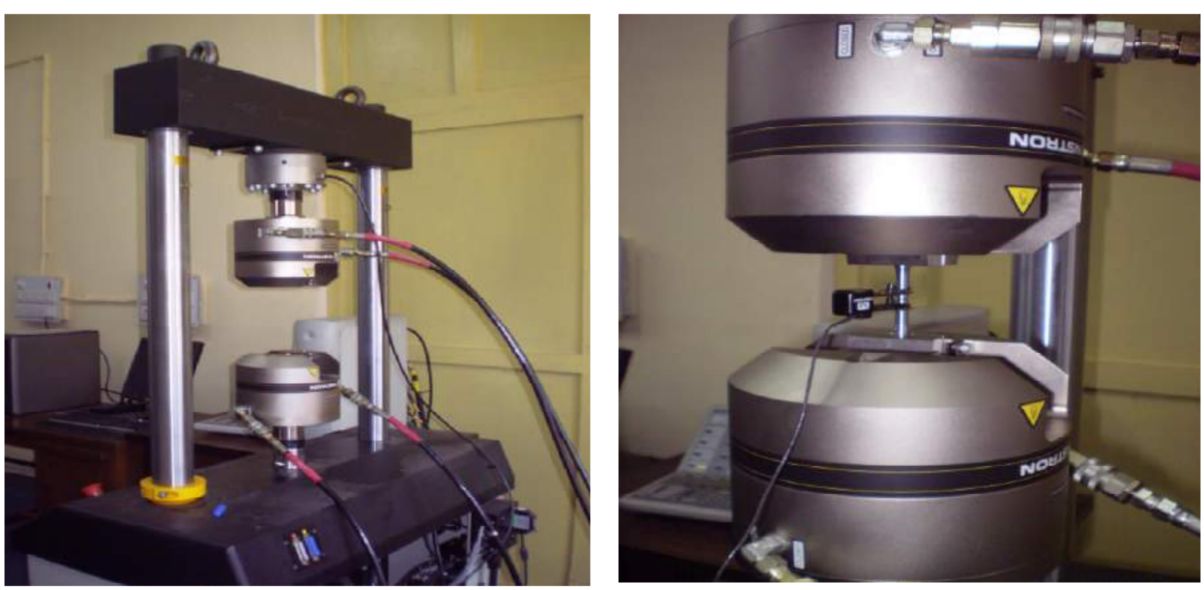


Fig 3:Experimental setup

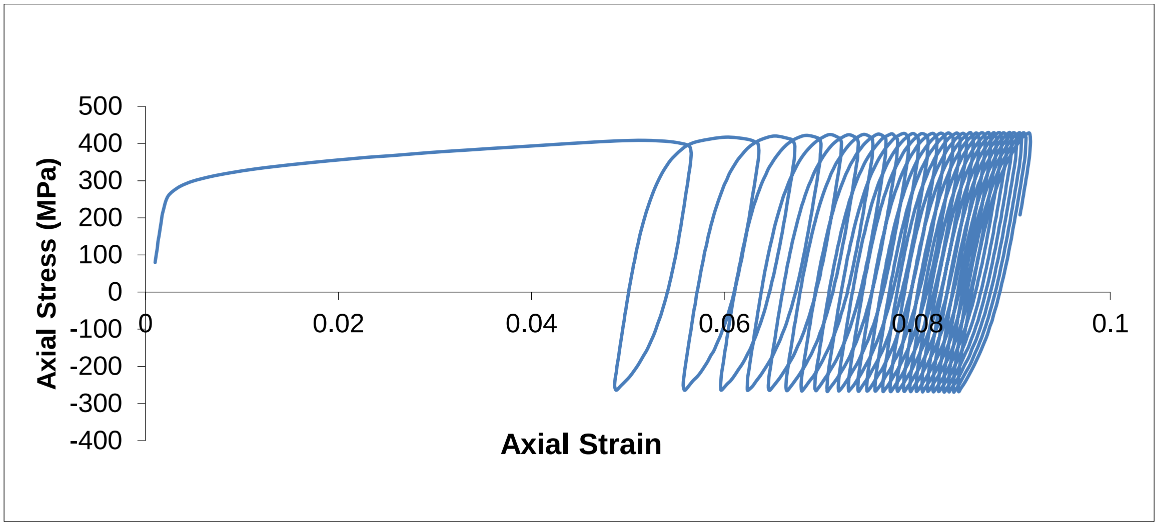
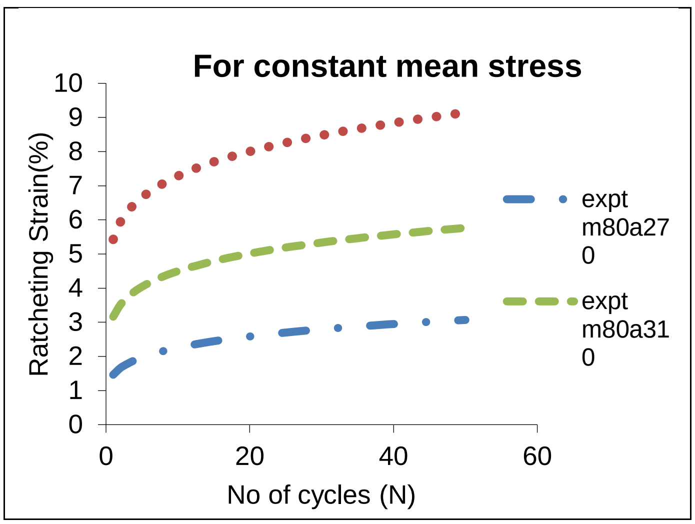


Fig.4: Axial ratcheting strain response for uniaxial stress-controlled cycles with mean stress (ratcheting load m80a350).



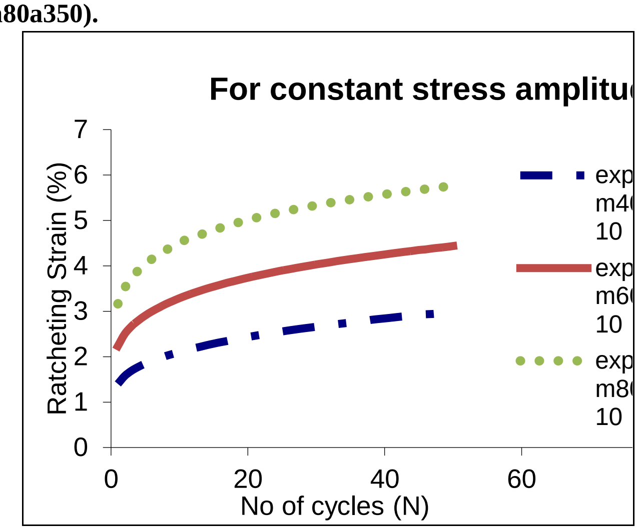


Fig.5:
(a) Experimental ratcheting strain vs. cycle for constant mean stress.
(b) Experimental ratcheting strain vs. cycle for constant stress amplitude

III. Cyclic plasticity modeling

The ratcheting behavior of the material is modeled using incremental plasticity theories. The plasticity calculations are based on the yield function, flow rule, hardening rule, and the yield surface's consistency condition. The plastic modulus calculation is coupled with the kinematic hardening rule through the yield surface consistency condition.

Von-Mises yield criterion: $\Phi(\bar{\sigma}-\bar{\alpha})=\left[\frac{3}{2}(\bar{s}-\bar{\alpha})(\bar{s}-\bar{\alpha})\right]^{1/2}=\sigma_C$

The stress tensor, the plastic strain tensor, $\bar{s}$ is the deviatoric stress tensor, $\bar{\alpha}$ is the as-back stress tensor, and is the yield surface's size.

Flow Rule:

The Plastic strain rate $\dot{\varepsilon}^{p}$ follows from the flow rules as

$$\dot{\bar{\varepsilon}}^{p} = d\varepsilon_{eq}^{p}\frac{\partial\Phi}{\partial\bar{\sigma}}$$

Here $d\varepsilon_{eq}^{p}$ is the equivalent plastic strain rate.

$$d\varepsilon_{eq}^{p} = \left|d\bar{\varepsilon}^{p}\right| = \left[\frac{2}{3}d\bar{\varepsilon}^{p} : d\bar{\varepsilon}^{p}\right]^{1/2}$$

Chaboche kinematic hardening rule.

$$d\bar{\alpha} = \sum_{i=1}^{3} d\bar{\alpha}_i \ , \ d\bar{\alpha}_i = \frac{2}{3}C_i d\bar{\varepsilon}^{p} - \gamma_i\bar{\alpha}_i d\varepsilon_{eq}^{p}$$

C's, γ's are model parameters of the Chaboche model.

Consistency condition:

During the plastic deformation, the stress vector remains on the yield surface. This leads to consistency equation, $\dot{\Phi}$ =0

Plastic modulus H is calculated using the consistency condition and is given by the relationship

$$H = \sum_{i=1}^{3} H_i$$

Where $H_i = C_i - \gamma_i\left(\bar{\alpha}_i : \frac{\partial f}{\partial\bar{\sigma}}\right)$

Table

Constitutive model parameters determination using manual inspection and GWOfor real response

Parameter	Manual calculation	GWO	Parameter	Manual calculation	GWO
$C_{1,(}$MPa)	75000	71555	γ_1	1500	1486
C_2 (MPa)	35000	36236	γ_2	348	325
C_3 (MPa)	4000	4569	γ_3	0	0
Fitness Value		Manual calculation			GWO
Uniaxial ratcheting fitness		0.0958			0.0374

IV. Finite element simulation of ratcheting behavior

To study materials' ratcheting behavior, the stress-controlled test with non zero mean stress is conducted on a round bar specimen. Chabochekinematic hardening model has been used for finite element simulation. The GWO optimization procedure has minimized the objective function, and the results are compared with that of the results obtained using a manual procedure. The comparison of experimental results with the simulation result obtained using the manual procedure and GWO approach for saturated stress-strain loop of ±1.0% strain amplitude using Chaboche's sharpening model is shown in Figure-6. The results obtained using the GWO approach shows better matching with the experimental results than the result obtained using manual calculation procedure.

Figure-7show the result obtained using Chaboche KH law using both approaches.GWO approach gives a better ratcheting rate than the normal approach for the ratcheting load.

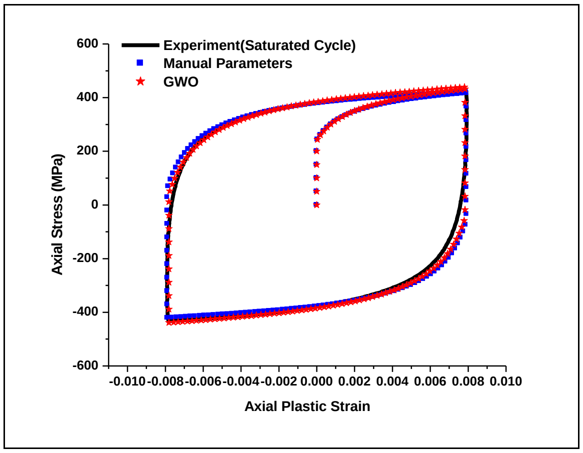


Fig 6 Stable stress-strain hysteresis loop for ±1.0% strain amplitude using Chaboche rule (ABAQUS results).

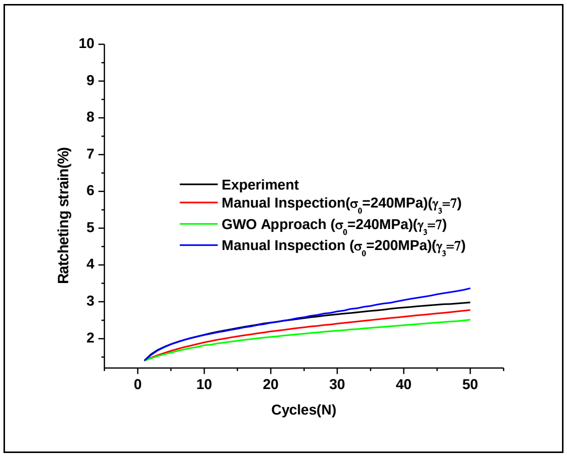


Fig 7: variation of ratcheting strain with cycles for ratcheting load of m40a310.

V. Conclusion

Anew meta-heuristics optimization method named Grey wolf optimization (GWO) was developed in this research work to perform material parameter identification of an SS 316 stainless steel. Moreover,stress-controlled low cycle fatigue tests at various combinations of mean stress and amplitude stress are performed to obtain an experimental database on this material. The Chaboche kinematic hardening material model is used to describe material behavior. The simulation results clearly show that the GWO algorithm can fit the experimental behavior. It is also observed that the GWOprovides a better ratcheting rate for the case of uniaxial ratcheting in comparison with the manual approach.

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