Modeling and Simulation of SS 316 Stainless Steel for LCF Behaviour

J.Shit*
Department of Mechanical Engineering,
Purulia Government Engineering College,
Purulia- 723103,India
jagabandhushit@rediffmail.com

Abstract: This paper deals with Finite Element simulation to characterize the LCF behavior of SS316 stainless steel. Calibration and truing of LCF parameters of the material SS316 are done from the experimental results. Non linear version of Ziegler kinematic hardening material model is used to address the stable hysteresis cycles of the material. Cyclic hardening phenomenon in the transition cycles from virgin state to saturation state is addressed by introducing cyclic hardening in the material model. The elastic plastic FE code ABAQUS is used for finite element simulation of LCF behavior where in ABAQUS material model is plugged in. In this work the plastic modulus formulation with zeigler kinematic hardening rule and exponential isotropic hardening rule have been used. Loop areas have been generated based on the cyclic elastic-plastic stress-strain response in order to identify the fatigue damage parameter. The cyclic plastic stress-strain responses were analyzed using the incremental plasticity theories and the results obtained from FE simulations have been compared with the experimental results at different strain amplitudes.

Keywords: *Cyclic hardening, elastic-plastic finite element, incremental plasticity, Kinematic hardening, LCF, plastic modulus.*

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I. Introduction

SS316 stainless steel used for pressure vessels and piping in the nuclear power-generating industry as because the material is having good strength, high ductility & fracture toughness and high heat resistance capacity. Low cycle fatigue [1-3] must be considered during design of nuclear pressure vessels, steam turbines and other type of power machineries where life is nominally characterized as a function of the strain range and the component fails after a small number of cycles at a high stress, and the deformation is largely plastic. LCF & HCF behaviour of SS316 was investigated by Wong et al.[4]. High temperature LCF tests on SS316 were investigated by Martin-Meizoso et al. [5] at temperature 600-625^{0}C. Experimental observation shows that various cyclic plastic behavior [6-9] of the material. Those are i.) Bauschinger effect ii.) Cyclic hardening [10] iii.) Mean stress relaxation [9].

II. Material characterization

2.1 Low cycle fatigue tests

The strain-controlled tests were performed on the specimens for symmetric tension-compression strain cycles with the strain limits $\Delta\in$= ±0.50%, ±0.60%,±1.00%. During tests sinusoidal wave shape was used to control a constant strain rate of 10^{-2}/s. Tensile peak stress with number of cycles for different strain amplitude were observed. Hysteresis loops stabilize after about 30 cycles and the material arrives at an equilibrium condition for the imposed strain amplitude.

III. Numerical simulation

3.1 Modeling of cyclic plasticity:

The cyclic behavior of the material was modeled using Von mises yield function, flow rules and the nonlinear isotropic-kinematic hardening model and consistency condition as follows:

3.1.1 Yield Function: - The Von mises yield function is as follows.

$$\Phi = \frac{3}{2}\left(S_{ij} - \alpha_{ij}\right)\left(S_{ij} - \alpha_{ij}\right) - \sigma_c^2 = 0\,,\quad \sigma_c = \text{Current flow stress of matrix material,}$$

S_{ij} = deviatoric part of stress tensor, $\sigma_{ij} = S_{ij} + \sigma_m \delta_{ij}$, σ_m = Mean Stress, α_{ij} = back stress tensor, also deviatoric in nature,

3.1.2 The Flow Rule:

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

$$\dot{\varepsilon}_{ij}^{p} = \dot{\bar{\varepsilon}}^{p} \frac{\partial \Phi}{\partial \sigma_{ij}}$$

Here, $\dot{\bar{\varepsilon}}^{p}$ is a scalar multiplier or equivalent plastic strain rate.

Which yields $\dot{\bar{\varepsilon}}^{p} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{p}\dot{\varepsilon}_{ij}^{p}} = \lambda\left[\frac{2}{3}\frac{\partial \phi}{\partial \sigma_{ij}}\frac{\partial \phi}{\partial \sigma_{ij}}\right]^{\frac{1}{2}}$

3.1.3 Non-linear isotropic/kinematic hardening model:

When temperature and field variable dependencies are omitted, the hardening law is

$$\dot{\alpha} = C\frac{1}{\sigma_c}(\sigma - \alpha)\dot{\bar{\varepsilon}}^{p} - \gamma\alpha\dot{\bar{\varepsilon}}^{p}$$

Where, C and γ are material parameters that is calibrated from cyclic test data. The isotropic hardening behavior of the model defines the evolution of the yield surface size, σ_c as a function of the equivalent plastic strain, $\dot{\bar{\varepsilon}}^{p}$. This evolution can be introduced by specifying σ_c directly as a function of $\dot{\bar{\varepsilon}}^{p}$.

Now the simple exponential law is

$$\sigma_c = \sigma|_0 + Q_\infty\left(1 - e^{-b\bar{\varepsilon}^{p}}\right)$$

Where, $\sigma|_0$ is the yield stress at zero plastic strain and Q_∞ and b are material parameters.

3.1.4 Consistency condition:

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

Finally, the elastic–plastic tensor, D_{ijkl}, is represented as

$$: D_{ijkl} = E_{ijkl} - \frac{1}{H}E_{ijkl}\frac{\partial \phi}{\partial \sigma_{mn}}E_{klop}\frac{\partial \phi}{\partial \sigma_{op}}$$

IV. Finite element simulation:

The FE simulation of the model is implemented on a round bar specimen under strain controlled tension compression loading. This article aims at simulating various experimental observations for different strain amplitudes. The Ziegler kinematic hardening laws have been used for simulation. The non-linear version of Ziegler kinematic hardening rule plugged in elasto plastic finite element FE code ABAQUS. The cyclic loading is plastic strain controlled. The saturated values of Ziegler kinematic hardening coefficients as obtained from experimental saturated loop of 1.0% strain amplitudes are used to simulate the hysteresis loops, peak stress vs. cycles and loop areas of all the strain amplitudes. Fig.1 (a&b), and Fig.2(a&b) shows the simulated result for hysteresis loops. It is found that the simulated results match satisfactorily with the experimental results for the material SS-316 stainless steel. Fig.3(a) and Fig.4(b) shows peak stress vs. cycles. Here the simulated results follow the experimental result in a better way. The cyclic hardening rate matches. Fig.5 shows loop areas (between stress and strain) obtained by using Ziegler coefficients in commercial FE package ABAQUS and the results are compared with experimental values. Fig.5 Shows that matching is acceptable in engineering sense.

Kinematic Hardening Coefficients (Saturated values)

C=70000 MPa, γ=1700

Isotropic Hardening Coefficients

Q_{∞} =45 b =10 .0

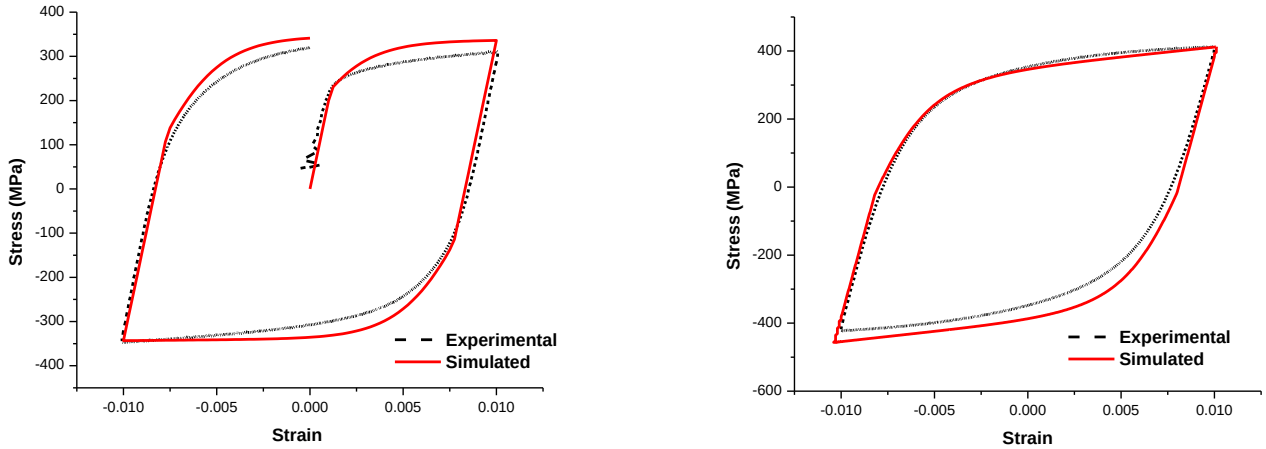

Fig.1 (a&b): Strain amplitude ± 1.0% for 1st and saturated loop.

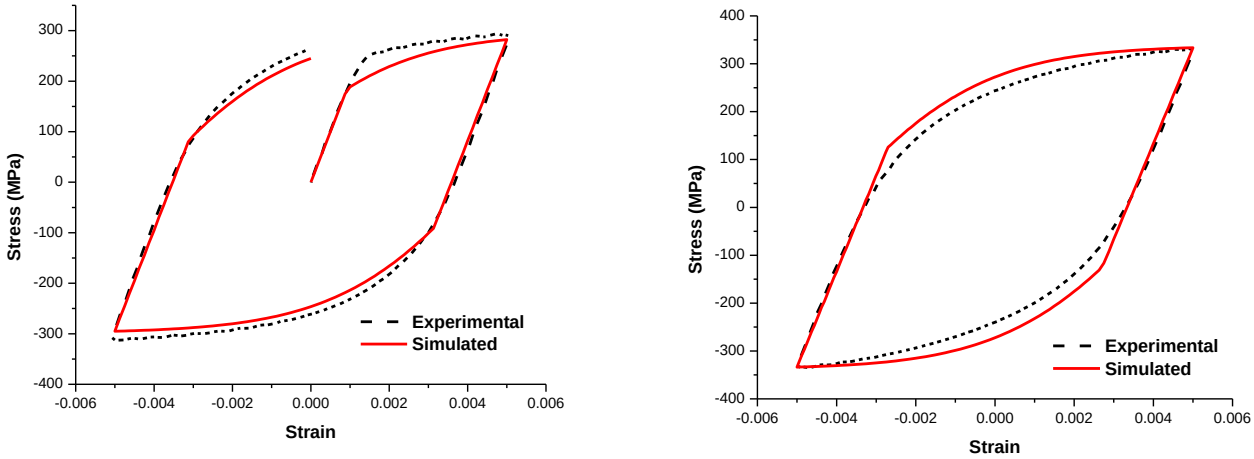

Fig.2 (a&b): Strain amplitude ± 0.5% for 1st and saturated loop.

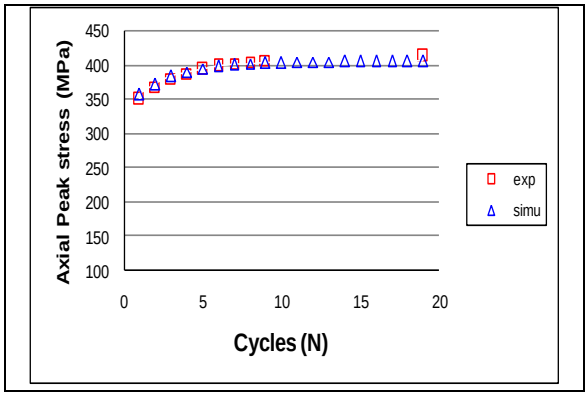

Fig.3 : Strain amplitude ± 1.0%.

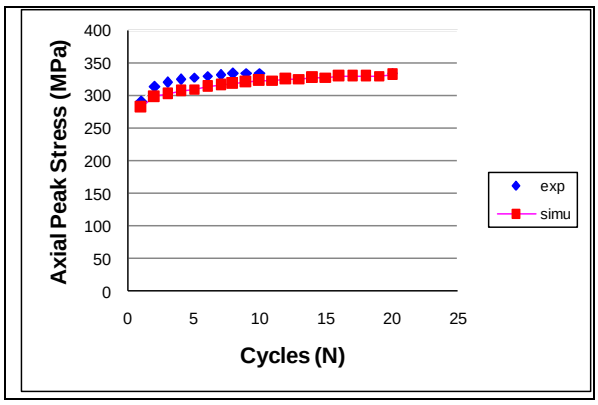

Fig.4: Strain amplitude ± 0.5%.

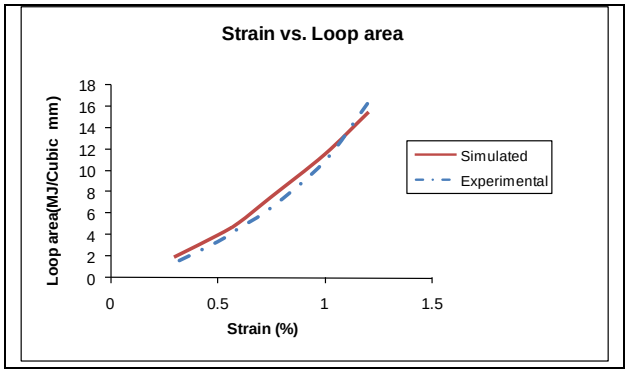

Fig.5: Loop area (between stress and strain) plot.

V. Discussion & Conclusions:

The present work is an attempt for characterization of FE simulation of various cyclic plastic behavior of SS316. Simulation of hysteresis loops for various strain amplitudes were made by ziegler's non linear material model by elasto-plasto finite element method by using finite element package, ABAQUS. Comparison between simulated and experimental loop is satisfactory is engineering sense. But there is some mismatch at the elastici-plastic knee region. This is because of using ziegler's single segmented non linear kinematic hardening law which has the same deficiency as the single segmented Armstrong Frederick law, however results can be improved by using Chaboches 3 segmented non linear kinematic hardening model. The next attempt of this study is to simulate peak stress value with no. of cycles for various strains amplitudes. Fig.3 and Fig.4 shows the simulated peak stress vs cycles as obtained by using ziegler kinematic hardening. It is seen that the matching is satisfactory in engineering sense. The loop areas are calculated to compare with the experimental results. Fig.5 shows that matching is acceptable in engineering sense.

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Biographical notes

- **Dr. Jagabandhu Shit** is an Associate Professor of Mechanical Engineering, Purulia Govt. engineering College, West Bengal (India). He is engaged in teaching and research activities since the last 12 years. His field of specialization is Fatigue, Fracture and Damage analysis of structure. He is doing his research work in the area of LCF and ratcheting. He has published several papers in various national, international conferences and journals. He has completed his PG from Mechanical Engineering Department Jadavpur University, West Bengal (India). He is the fellow member of professional bodies: The institution of Engineers (India) (F: 121266-0) and The Indian society for Technical Education (LM 110541).