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Predicting the Nonlinear Material Behaviour under Monotonic and Cyclic loading of SA333 and SS3304 Steels

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ABSTRACT
Nonlinearity naturally arises in a true, rigorous mathematical formulation of physical problems. One of the most common nonlinearity is the material nonlinearity where the stress-strain response behaves nonlinearly. The main objective of this paper is to predict the material nonlinearity with the use of constitutive material model. To this end, the specimen is modeled with the eight nodded solid elements. One end of the specimen is fixed while the prescribed displacement is specified at the other end. The Chaboche model parameters are fitted first by matching the experimental stress-strain curve [4] with the finite element simulations. After that the response of the specimen is predicted when subjected to different displacement amplitudes i.e. completely reversed loading, cyclic tension loading and fluctuating ramp loading

***Keywords*:** Chaboche parameter, Finite element method, Nonlinearity, Stress, Stain

I. INTRODUCTION

In structural mechanics, the most common type of analysis is the linear static analysis where the displacements are assumed to be small. However, at higher load a number of nonlinearities may be encountered. One of the most common of this is material nonlinearity where the stress-strain. Other common nonlinearities include those arising from the significant changes in the geometry during loading. Both material and geometric nonlinearities arise as a result of the structure being subjected to forces of significant magnitude. Material nonlinearity itself may be divided into nonlinear elasticity and Elasto-plasticity. In nonlinear elasticity the stress-strain relation is nonlinear but otherwise the behaviour follows that of linear elasticity, that is, no distinction is made between loading and unloading except for the sign. This is in contrast to what is the case with plastic or Elasto-plastic materials, where irreversible strain occurs. For low stress levels, both materials follow linear stress-strain levels. This is followed by decrease in stiffness as the stress increases. If the stress is reduced further, the non-linear elastic material will follow the same stress-strain curve as in loading, whereas unloading of the Elasto-plastic material leads to a new branch on the stress-strain curve where the material is again elastic. Another important aspect in real life arises when the structures are subjected to cyclic loading. Most load bearing components in engineering are subjected to cyclic loading and the cyclic plastic deformation of the material is unavoidable. Cyclic plasticity deals with the nonlinear stress-strain response of the material when subjected to cyclic external loading. Plasticity models or constitutive equations are mathematical relations describing the stress-strain response of a material subjected to external loading. The load excursion on a component can be either in terms of stress (as in load based design) or strain (as in displacement based design) and when the magnitude of stress/strain reversal is sufficient, cyclic plastic deformation will occur. Alteration in the stress-train response of a material subjected to cyclic loading is referred as cyclic hardening/ softening behavior. It is often studied by testing the material under fully reversed stress or strain controlled cycling. With controlled strain amplitude, a material is said to have exhibited cyclic hardening/softening when an increase/decrease in stress amplitude with progressive cycles is observed [1-6]. Under stress controlled cycling, the hardening/softening can be related to the increase/decrease in the strain amplitude over a period of time [2, 4]. In general a hard material is expected to cyclically soften and a soft material is expected to cyclically harden.

Despite the extensive work that has been conducted on cyclic plasticity, many questions and difficulties exist. Accurate modelling of the cyclic plasticity is still difficult. Finite element analysis can be used to capture the nonlinearities of the material. The main objective of this study is to predict the material nonlinearity using FEM.

II. CONSTITUTIVE MODEL

Non linear kinematic hardening model proposed by Chaboche [7] is a superposition of three Armstrong and Frederick hardening models. The model can be written in the

$$d\alpha = \sum_{i=1}^{3} d\alpha^{i} \qquad (1.1)$$

$$d\alpha^{i} = \frac{2}{3}C_i d\varepsilon^{p} - D_i\alpha^{i}dp \qquad (1.2$$

$$d\alpha^{i} = \frac{2}{3}C_i d\varepsilon^{p} - D_i\alpha^{i}\,|d\varepsilon^{p}_{eq}| \qquad (1.3)$$

where C_i is kinematic hardening coefficient, D_i is kinematic hardening exponent, $d\varepsilon^p$ is the plastic strain increment tensor and α is a back stress tensor. Loading part of the stress strain curve can be representing

$$\sigma = \sigma_0 + \sum_{i=1}^{3} \alpha^{i} \qquad (1.4)$$

where σ is a stress at any point and σ_0 is a cyclic stress. Saturated value of the back stress in the model is given as a summation of all three individual saturated value of decomposed back stress, as expressed

$$\alpha_s = \frac{C_1}{D_1} + \frac{C_2}{D_2} + \frac{C_3}{D_3} \qquad (1.5)$$

Where α_s is the saturated value of the back-stress. Some suggestions are given by Chaboche to determine the parameters like coefficients and exponents. He suggested that material parameters are obtained by producing the 1.6% stable hysteresis loop at LCF under stress (or strain) controlled loading and the value of C_1 is determined from the slope of stress-plastic strain curve of loading branch of stable hysteresis loop at cyclic yield point. Corresponding D_1 value should be large enough such that α_1 saturate immediately. The value of C_3 is determined from the slope of stress-plastic strain curve of unloading branch of stable hysteresis loop at cyclic yield point. C_2 and D_2 are estimated by trial and error so that Equation (1.6) is satisfied, $C_1 > C_2 > C_3$ and $D_1 > D_2 > D_3$

$$\frac{C_1}{D_1} + \frac{C_2}{D_2} + \sigma_0 = \sigma - \frac{C_3}{2}\left(\varepsilon^{p} + \varepsilon^{p}_{yc}\right) \qquad (1.6)$$

where ε^{p}_{yc} is the plastic strain at the cyclic yield point in loading branch of hysteresis loop. The chemical and constitutive properties for both materials are shown in table I and table II respectively. The constitutive parameters are given in table III

Table I Chemical Composition of Materials

Material	**C**	**Mn**	**Si**	**P**
SA333	**0.18%**	**0.90%**	**0.25%**	**0.02%**
SS304	**0.08%**	**2%**	**1%**	**0.45%**

Table II Mechanical Properties of Materials

Material	**UTS (MPa)**	**E (GPa)**	**υ**	**σ_0**
SA333	**429**	**200**	**0.3**	**225**
SS304	**505**	**200**	**0.29**	**215**

Table III Constitutive Parameters of Materials

Material	**C_1 (GPa)**	**C_2 (GPa)**	**C_3 (MPa)**	**D_1**	**D_2**	**D_3**
SA333	**140**	**25**	**1950**	**1750**	**238**	**0**
SS304	**6.3**	**4.1**	**1650**	**8950**	**500**	**6**

III. FE MODEL

For the present study, the specimens for monotonic tension have a test section diameter of 10 mm and gage length of 50 mm. The specimen is meshed using 8-noded solid elements wherein one end of the specimen is fixed while the prescribed displacement is specified at the other end. Three different cases are simulated especially (a) cyclic tension (b) fluctuating ramp and (c) cyclic strain and the results are compared with the experimental data [6]. Fig. 1 shows the geometrical dimensions along with the FE mesh of the test specimen. SA333 and SS304 steel material are used for the analysis. The material properties are given in table I.

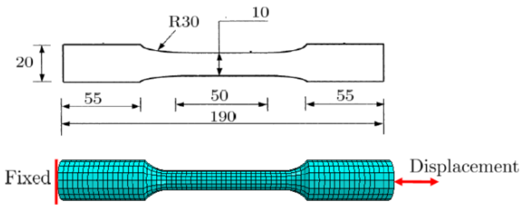
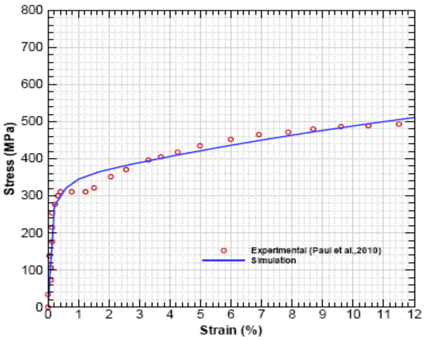


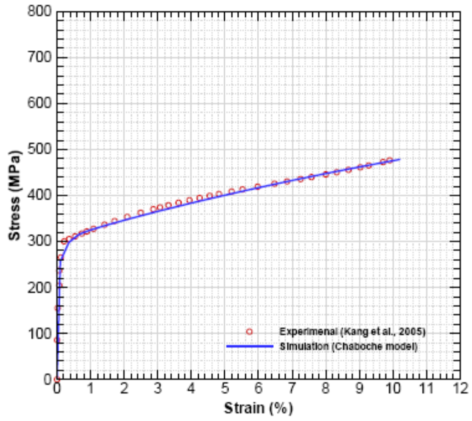
Fig.1 Geometrical dimensions and FE mesh

IV. BEHAVIOUR UNDER MONOTONIC LOADING

The stress-strain results obtained from the experiment of SA333 (see Fig. 2(a)) material shows linear relation till approximately 0.4% of strain and then shows at region of constant stress of 310 MPa for 1.75% strain and strain hardening region till 12 % of the strain.



(a)



(b)

Fig. 2 Experimental and simulation results of monotonic tension loading for:
(a) SA333, and (b) SS304.

The results obtained from the FE analysis (blue line) predicts the same behaviour with reasonable accuracy which reflects that the constitutive parameters extracted from cyclic experiments can capture the response of the material under monotonic loading as well. The flat region observed in the experiments is not captured well from FE simulations. One of the reasons of this mismatch could be that the microstructure behaviour like void formation, dislocation etc is not modeled in the simulations. The tensile behaviour of SS304 is slightly different than SA333 in which the linear relation between stress and strain is observed only up to 0.1 % and after that the material is hardened till 10 % (see Fig. 2(b)).

V. BEHAVIOUR UNDER CYCLIC LOADING

The behaviour of the material is also predicted under two different strains loading especially cyclic straining with two different amplitudes as shown in Fig 3. Prescribed displacement of 0.5 mm is applied in all cases reported at one end of the specimen while the other end is fixed.

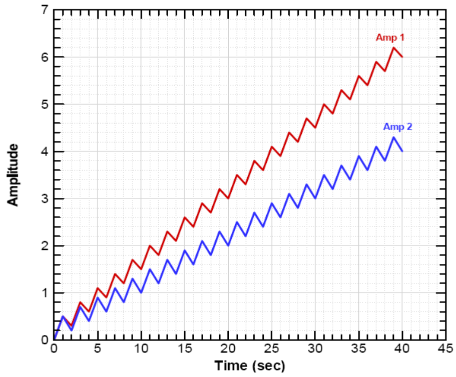
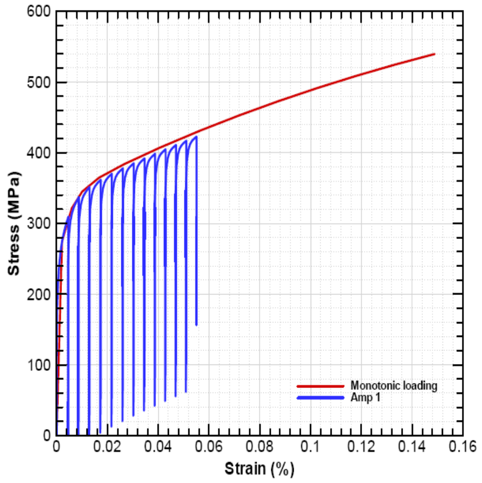
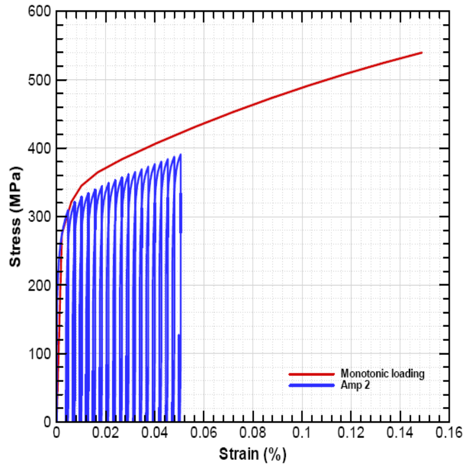


Fig.3 Cyclic straining amplitude

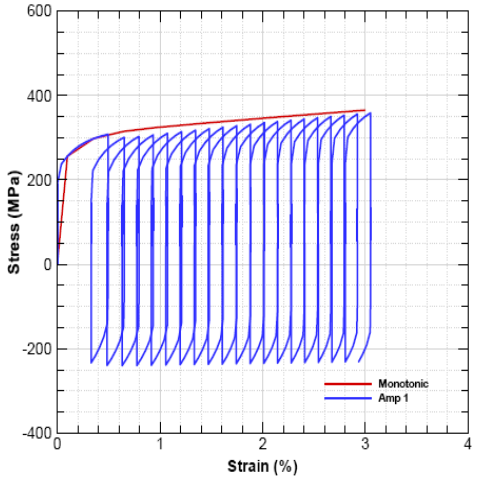


(a)

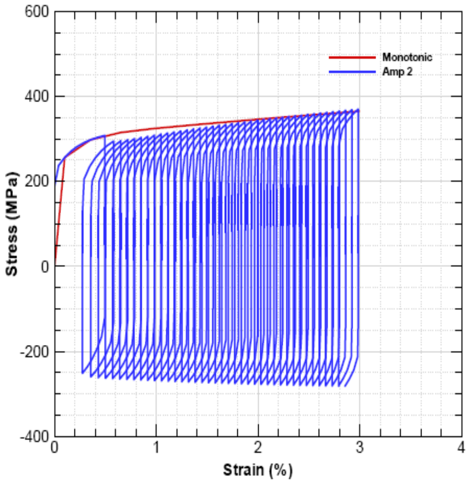
The material is tested under cyclic tension (as shown in Fig. 3a), in which tensile peak strain increases by $\Delta\varepsilon$ (= 0.1 %) every cycle while $d\varepsilon$ (=0.4%) is constant. For amplitude 2, tensile peak strain increases by $\Delta\varepsilon$ (= 0.05 %) every cycle while $d\varepsilon$ (=0.45%) is constant.



(b)



(c)



(d)

Fig. 4 Material response for SA333 under (a) amplitude 1, (b) amplitude 2 and for SS304 under (c) amplitude 1, (d) amplitude 2

Fig. 4 shows the experimental results. It is seen from Fig. 4(a) and (b) that the tensile peak points in cyclic tension almost lie on the monotonic curves of the material when subjected to amplitude 1 while for amplitude 2; the tensile peak is below the monotonic curve. Here it is noted that accumulated plastic strain continues to increase with the progress of cyclic tension, It is, then, suggested that accumulated plastic strain has negligible influence on the strain softening/hardening in cyclic tension, if $\Delta\varepsilon$ is small. Similar results are obtained for the material SS304 (see Fig. 4(c)-(d)).

VI. CONCLUSION

For the present study, the nonlinear response of two different grades steel material is captured using the finite element method. To check the efficacy, FE results are compared with the experimental results in both the cases for monotonic loading. It can be concluded from the simulation results of cyclic loading that during each strain cycles, a hysteresis loop is generated in the response. In SA333 steel the width of the loop is smaller compared to SS304 steel. Hence the ratcheting strains (i.e. plastic strain accumulation during every cycle) is more in SS304 steel compare to SA333.

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