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An improved nonproportional cyclic plasticity model for multiaxial low-cycle fatigue and ratcheting responses of 304 stainless steel

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An existing cyclic plasticity constitutive model is enhanced to simulate low-cycle fatigue and ratcheting responses of 304 stainless steel (SS) under proportional and various nonproportional loading cycles. Nonproportional loading and multiaxial ratcheting parameters, and strain range dependent cyclic hardening/softening modeling features are incorporated into a modified Ohno–Wang model to enhance its uniaxial and multiaxial loading responses. The improved constitutive model is incorporated in the commercial Finite Element Code ABAQUS through its user defined subroutine UMAT and the responses of 304 SS tubular specimen from literature have been simulated. The proposed model has demonstrated good correlation with uniaxial and different types of multiaxial fatigue and ratcheting responses. Two types of multiaxial loading cycles are studied; the first included axial and torsion cycles along different loading paths, and the second included steady internal pressure and axial strain or stress cycles. The axial–torsional loading cycles demonstrated axial and/or shear strain ratcheting, whereas the internal pressure-axial cycles demonstrated axial and/or circumferential strain ratcheting. Complex interactions between ratcheting strains in different directions along with the rate of ratcheting are simulated well by the improved Ohno–Wang model.

1. Introduction

Engineering components and structures are often subjected to multiaxial cyclic loading in the plastic range of the material. Therefore, prediction of cyclic plasticity responses at critical locations is essential for predicting fatigue life of components. In this study, 304 stainless steel (SS) uniaxial and multiaxial low cycle fatigue and ratcheting responses are considered for improving simulation capability of a modified Ohno Wang model (Chen and Jiao, 2004). Ohno Wang model (Ohno and Wang, 1993a,b) is a multilinear model incorporating modified Armstrong and Frederick (1966) type kinematic hardening rule following the superposition concept of Chaboche et al. (1979, 1986). Many modified versions of the Ohno–Wang and Chaboche models have been proposed in order to improve their ratcheting strain accumulation (Chaboche and Nouailhas, 1989a,b; Chaboche, 1991, 1994; Jiang and Sehitoglu, 1994; Abdel-Karim and Ohno, 2000; Yoshida, 2000; Yoshida and Uemoni, 2002; Kang and Gao, 2002a; Bari and Hassan, 2002; Kang et al., 2004).The important aspects of multiaxial loading simulation using the Chaboche and two surface models have been described by Bari and Hassan (2000, 2001, 2002). They demonstrated

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Nomenclature

$d\underline{\sigma}$	increment of stress tensor
$d\underline{\varepsilon}$	increment of total strain tensor
$d\underline{\varepsilon}^e$	increment of elastic strain tensor
$d\underline{\varepsilon}^p$	increment of plastic strain tensor
E	elastic modulus
f	Von Mises yield function.
dp	magnitude of plastic strain increment
$\underline{s}$	deviatoric part of the stress tensor
$d\underline{a}$	increment of total backstress tensor
$\underline{a}^{(i)}$	components of total deviatoric backstress tensor
$\lvert\underline{a}^{(i)}\rvert$	magnitude of decomposed backstress tensors
$\underline{a}$	deviatoric total backstress tensor
$\underline{n}$	normal to the yield surface
$C^{(i)}, \gamma^{(i)}, r^{(i)}$	kinematic hardening coefficients
$C_{i0}^{(i)}, r_{i0}^{(i)}, z_0^{(i)}$	initial values of kinematic hardening coefficients
$m^{(i)}$	Ratcheting parameter
δ'	Multiaxial parameter
D'_δ	coefficient for the evolution of δ'
$\delta'^{\infty}(q)$	saturated value of δ'
A	scalar nonproportionality parameter
a_{1d}, b_{1d}	material constants for evolution of ratcheting parameter
c_d	cross hardening parameter
b_{c0}, b_{c1}	material constants for evolution of cross hardening parameter
$d_{gc}^{(i)}, d_{gr}^{(i)}, k_{gc}^{(i)}, k_{gr}^{(i)}, d_{gk}^{(i)}$	material parameters for evolution of cyclic hardening parameters
$k_{gp}^{(i)}, d_z^{(i)}, c_z^{(i)}, e_z^{(i)}, k$	material parameters for evolution of cyclic hardening parameters
β	center of memory surfaces
q	size of memory surfaces
F	evolution function for memory surface
$\underline{n}^*$	normal to the memory surface
q_p, q_N	target value of the size of memory surface under proportional and
$b_1 to b_6,\ c_1 to c_4,\ b$	material parameters for evolution of memory surface nonproportional loading
η, ξ, m	material parameters for evolution of memory surface
$\underline{\underline{C}}$	fourth order tensor for nonproportionality parameter of Tanaka (1994)
c_c	parameter for rate of increment of $\underline{\underline{C}}$
σ_0	size of initial yield surface
σ_y	size of current yield surface
σ_{xc}	amplitude of axial strain in biaxial internal pressure tension loading
σ_θ/σ_y	ratio of circumferential stress to yield stress in biaxial loading
$\langle\rangle$	MacCauley bracket
$H(F)$	Heaviside function
$\underline{1}$	second order identity tensor
$:$	inner product between tensors
$\otimes$	dyadic product of tensors

that if the model parameters are derived only from uniaxial responses the constitutive model fails to predict ratcheting response under multiaxial loading.

Many researchers (McDowell, 1995; Jiang and Sehitoglu, 1996 a,b; Voyiadjis and Basuroychowdhury, 1998) have proposed incorporation of multiaxial parameters in Chaboche and Ohno–Wang models to reduce the over prediction of multiaxial ratcheting. However these modifications failed to improve multiaxial ratcheting simulation as demonstrated by Bari and Hassan (2002). They incorporated the kinematic hardening rule of Delobelle et al. (1995) into the Chaboche model (1986, 1991) to significantly improve the multiaxial ratcheting simulations. Constitutive model improvement for simulation of ratcheting under various multiaxial loading paths has been studied by Hassan et al. (1992a,b), Hassan and Kyriakides (1994b), Jiang and Sehitoglu (1994), Corona et al. (1996), Portier et al. (2000), Bocher et al. (2001), Igaria et al. (2002), Kang et al. (2002a, 2002b, 2004) and many others. Incorporating nonproportional modeling features are demonstrated to be more rational method for improving multiaxial ratcheting simulation (McDowell, 1985, 1987; Tanaka et al., 1985a, 1985b; Benallal and Marquis, 1987; Tanaka and Okuchi, 1988; Tanaka, 1994; Jiang and Zhang, 2008; Hassan et al., 2008; Krishna et al., 2009).

Hassan et al. (2008) had shown that Benallal and Marquis (1987) model incorporated into the modified Chaboche model (Bari and Hassan, 2000) is able to simulate multiaxial ratcheting responses quite well when the degree of nonproportionality does not change abruptly. The simulation results deviate considerably from the experimental observation when there is a rapid change in loading direction. The deficiency is explained by Hassan et al. (2008) that the memory feature is not included in the nonproportionality formulation of Benallal and Marquis (1987). Tanaka and Okuchi (1988) and Tanaka (1994) proposed a fourth order tensor as measure of nonproportionality which had resulted in better simulations of additional cyclic hardening (Jiang and Kurath, 1997; Zhang and Jiang, 2008), ratcheting (Portier et al., 2000; Hassan et al., 2008; Krishna et al., 2009) and cross-hardening (Zhang and Jiang, 2008) because of the strain memory modeling feature. This fourth order tensor depicts the dislocation structures generated due to cross hardening (Tanaka, 1994) and thereby incorporates memory of the prior loading history (Jiang and Kurath, 1997).

Nouailhas et al. (1985) described anisotropic evolution of yield surface due to cross hardening effect of nonproportional loading. They observed that the expansion of yield surface was higher along the perpendicular directions compared to the direction of prior loading. This phenomenon was attributed to be the primary reason for manifestation of the cross hardening in the material. The minimum hardening has been observed under proportional loading path in either axial or shear directions where as maximum hardening occurred under 90 degree out of