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Ratcheting assessment of steel samples under various non-proportional loading paths by means of kinematic hardening rules

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ABSTRACT

The present study predicts ratcheting response of 1045 and 1Cr18Ni9Ti tubular steel samples using nonlinear kinematic hardening rules of Ohno-Wang (O–W), Jiang–Sehitoglu (J–S), McDowell, Chen–Jiao–Kim (C–J–K) and newly modified model based on the hardening rule of Ahmadzadeh–Varvani (A–V) under various multiaxial loading histories. The modified hardening rule with less complexity holds components of backstress unity vector $\overline{a}/|\overline{a}|$ and the normal vector to the yield surface $\overline{n}$ in its dynamic recovery to encounter non-proportionality. The components in the Macaulay brackets $\langle d\overline{\varepsilon}_p \cdot \overline{a}/|\overline{a}|\rangle$ possessing different directions enable the hardening rule to track different directions under multiaxial stress cycles. Coefficient γ_2 controls the ratcheting rate and is regulated by term $(2-\overline{n}.\overline{a}/|\overline{a}|)$ to further lower the ratcheting strain curve. Term $\langle\overline{n}.\overline{a}/|\overline{a}|\rangle^{1/2}$ in the dynamic recovery prevents ratcheting plastic shakedown as stress cycles progress.

The O–W, J–S and McDowell models persistently overestimated ratcheting curves in 1045 and 1Cr18Ni9Ti steel alloys for various multiaxial loading paths. Chen–Jiao–Kim modified the O–W model and possessed lower ratcheting results as compared with those predicted by other hardening rules. The predicted ratcheting curves through the modified model closely agreed with experimental data obtained under various multiaxial loading paths.

1. Introduction

Engineering components experiencing asymmetric stress cycles with non-zero mean stress accumulate an irreversible plastic deformation along with fatigue damage as the number of cycles progresses. For reliable design of engineering components and structures undergoing asymmetric stress cycles, ratcheting assessment of materials is always crucial. The successive and directional accumulation of plastic strain is referred as ratcheting strain. Both ratcheting and fatigue phenomena when they are coupled result in a severe damage leading to failure of components. Ratcheting phenomenon was first reported by Bairstow [1]. Ratcheting phenomenon has received considerable attention over the last few decades. Many researchers have investigated ratcheting response of various materials tested under stress-controlled conditions [2–12]. Several cyclic plasticity models have been developed to characterize ratcheting response of materials under various loading conditions. The coupled kinematic hardening rules [13–39] consist of the linear strain hardening and dynamic recovery terms have been mainly constructed on the basis of Armstrong–Frederick (A–F) [13].

Based on the concept of independent backstress components, Ohno and Wang [19] developed a multilinear hardening rule in which each backstress component has a critical state. To avoid producing closed hysteresis loops under uniaxial loading condition, the second version of O–W model was introduced [19] through a power-law function. To improve the capability of this model in predicting ratcheting strain under various loading conditions, the O–W models have been taken as the backbone of several hardening rules through modifications on the dynamic recovery part. Abdel-Karim [40] examined terms/variables introduced into the dynamic recovery term of the O–W model. Jiang and Sehitoglu [22] and McDowell [23] modified the exponent of the O–W model. Chen et al. [30] developed a model incorporating new factors associated with backstress and non-coaxiality of plastic strain rate in the second model of the O–W model. Ahmadzadeh–Varvani [34,35] modified the dynamic recovery term in Bower's kinematic hardening rule by means of limited number of coefficients to assess uniaxial ratcheting response of materials.

Multiaxial ratcheting response of materials becomes rather challenging as loading path and non-proportionality are coupled with the hardening rules. Non-proportional loading histories induce greater hardening than those of proportional resulting in slower rates in the ratcheting progress over multiaxial stress cycles [41]. To address the effect of complex loading paths and non-proportionality on ratcheting response of materials, several experimental studies have been conducted under both stress-controlled and the combined stress-controlled and strain-controlled conditions [41–46]. Hassan et al. [5,8,47] discussed capability of hardening rules in ratcheting assessment of

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Nomenclature

$\bar{a}$	total backstress tensor
$\bar{b}$	second kinematic variable in the A–V and the modified hardening rules
C	material constant in the A–V and the modified hardening rules
$d\,\bar{a}$	increments backstress tensor
dp	increment of accumulated plastic strain
$d\bar{s}$	deviatoric stress increment
$d\bar{\varepsilon}$	total strain increment
$d\bar{\varepsilon}^p$	plastic strain increment
$d\bar{\varepsilon}^e$	elastic strain increment
E	Young's modulus
G	Shear modulus
H_p	plastic modulus function
$\bar{I}$	unit tensor
$\bar{n}$	unit exterior normal to the present yield surface at the stress state
γ_1	material constant in the A–V and the modified hardening rules
γ_2, δ	stress level dependent constants in the A–V hardening rules
γ_2	calibrating coefficient in the modified hardening rule
ε_r	ratcheting strain
υ	Poisson's ratio
$\bar{\sigma}$	stress tensor
σ_a	stress amplitude
σ_m	mean stress
σ_0	size of yield surface
τ_a	shear stress amplitude
τ_m	mean shear stress

materials under multiaxial loading conditions and concluded that the non-proportionality effect is yet to be fully addressed and the shape of hysteresis curves and the evolution of yield surfaces over stress cycles are required to be accurately predicted.

The current study discusses multiaxial ratcheting of steel samples under various loading paths by means of the O–W, J–S, McDowell, C–J–K and modified hardening rules. The O–W, J–S, McDowell and C–J–K hardening rules with relatively complex structures and several coefficients were compared with the modified model with less complexity and number of coefficients. The O–W, the J–S and McDowell models overestimated the ratcheting strain of 1045 and 1Cr18Ni9Ti steel samples for various multiaxial loading histories, while the predicted curves of the modified model closely agreed with experimental data of steel samples over ratcheting stages.

2. Elements and framework of cyclic plasticity

Cyclic plasticity models consist of some common constituents strain increment, Hook's law, yield function and flow rule. Total strain increment is composed of both elastic and plastic strain components:

$$d\bar{\varepsilon} = d\bar{\varepsilon}^e + d\bar{\varepsilon}^p. \tag{1}$$

Elastic strain is defined by Hooke's law as:

$$\bar{\varepsilon}^e = \frac{\bar{\sigma}}{2G} - \frac{\upsilon}{E}(\bar{\sigma}.\bar{I})\bar{I} \tag{2}$$

where terms $\bar{I}$ and $\bar{\sigma}$ correspond respectively to unit and stress tensors. The plastic strain increment is obtained based on the associated flow rule as:

$$d\bar{\varepsilon}^p = \frac{1}{H_p}(d\bar{s}.\bar{n})\bar{n}. \tag{3}$$

Terms H_p and $d\bar{s}$ are the plastic modulus and the increment of deviatoric stress tensor respectively and $\bar{n}$ is the normal vector to the yield surface.

The hardening rule is the central part of cyclic plasticity theory defining the movement direction of yield surface in the stress space during plastic deformation. In the following section, a brief description of the O–W, J–S, McDowell, C–J–K and modified models is presented.

2.1. The Ohno-Wang (O–W) hardening rule

Ohno and Wang [19,20] developed a kinematic hardening rule on the basis of the critical state of the dynamic recovery term in the backstress equation. The total backstress in this hardening rule was defined based on the superposition of M independent backstress components suggested first by Chaboche [14] as:

$$d\bar{a} = \sum_{i=1}^{M} d\bar{a}_i \qquad (i = 1, 2, \ldots, M). \tag{4}$$

A critical value in each component ($i = 1, 2, \ldots, M$) caused its dynamic recovery term to be fully activated. The O–W model [20] was defined as:

$$d\bar{a}_i = \gamma_i\left[\frac{2}{3}r_i d\bar{\varepsilon}_p - \left(\frac{|\bar{a}_i|}{r_i}\right)^{m_i}\left\langle d\bar{\varepsilon}_p \cdot \frac{\bar{a}_i}{|\bar{a}_i|}\right\rangle \bar{a}_i\right]. \tag{5}$$

Exponent m_i in the O–W model is material dependent and is determined using uniaxial ratcheting data. By increasing the exponent m_i the predicted ratcheting curve by the O–W is shifted down under uniaxial loading, while the O–W model predicts larger ratcheting rate with smaller m_i. This model suffers the lack of terms and coefficients to regulate exponent m_i for multiaxial loading paths resulting in an overestimation of ratcheting. As exponent m_i approaches infinity, Eq. (5) turns to the initial O–W model and acts like a multilinear hardening rule resulting in the plastic shakedown after a slight overprediction in ratcheting [19]. Fig. 1 shows how a tensile uniaxial stress–strain curve is divided into several segments,

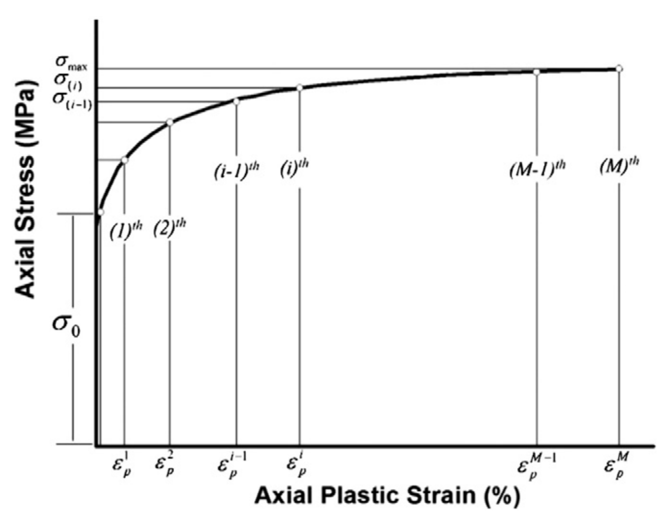

Fig. 1. The defined segments on the uniaxial cyclic stress–strain curve to determine the coefficients of the O–W hardening rule.