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Ratcheting of 304 stainless steel under multiaxial step-loading conditions

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ABSTRACT

The present study predicts ratcheting response of 304 tubular stainless steel samples undergoing multiaxial step-loading histories by means of nonlinear kinematic hardening rules of Ohno–Wang (O–W), Chen–Jiao–Kim (C–J–K) and the modified rule on the basis of Ahmadzadeh-Varvani (A–V) model. The plastic strain increment, $d\bar{\varepsilon}_p$, and the backstress unity vector $\bar{\alpha}/|\bar{\alpha}|$ as components in the MaCaulay brackets enabled the modified rule to track different ratcheting directions over multiaxial loading. Term $(2-\bar{n}\cdot\bar{\alpha}/|\bar{\alpha}|)$ further regulated coefficient γ_2 to account the effect of non-proportionality. The modified rule held term to prevent the model experiencing plastic shakedown.

Predicted ratcheting results by means of O–W model showed deviation from experimental data. Chen–Jiao–Kim modified the O–W model and possessed lower ratcheting results as compared with those of predicted by the O–W. The hardening rules enabled to assess ratcheting in different directions as loading steps possessed high–low sequence in the second and third steps. The choice of hardening rule to assess ratcheting of steel samples was found very much dependent on complexities involved with ratcheting algorithms, their constitutive equations and framework, coefficients, and Central Processing Unit (CPU) time required to run ratcheting programs over loading steps.

1. Introduction

For a reliable design of engineering components/structures subjected to step-loading histories, ratcheting assessment of materials becomes critically important. The successive and directional accumulation of plastic strain is referred as ratcheting strain. Ratcheting phenomenon was first reported by Bairstow [1]. This phenomenon has received considerable attention over last few decades [2–35]. Many researchers have investigated ratcheting response of various materials tested under stress-controlled conditions [2–12]. The coupled kinematic hardening rules [13–35] holding terms of linear strain hardening and dynamic recovery have been mainly constructed on the basis of Armstrong–Frederick (A–F) [13]. The capability of the coupled hardening rules has been highly dependent on coefficients defined in the dynamic recovery term. Chaboche [14] proposed a model with a threshold in the dynamic recovery term. He decomposed the A–F hardening rule to several parts at which backstress components worked independently. The threshold in the hardening rule was implemented by means of a term inside MaCaulay brackets to reduce the overall magnitude of ratcheting. During plastic deformation, this threshold converted the model from non-linear to linear hardening rule. Beyond this threshold, the recall term prevented plastic shakedown to occur. Bari and Hassan [36] achieved better simulation of uniaxial ratcheting strain while the model with threshold overpredicted ratcheting strain for multiaxial loading conditions. Ahmadzadeh–Varvani [34,35] modified the dynamic recovery term in A–F kinematic hardening rule by means of limited number of coefficients to assess uniaxial ratcheting response of materials.

Multiaxial ratcheting response of materials was found rather challenging as loading path and non-proportionality were coupled with the hardening rules. Non-proportional loading histories induced greater hardening than those of proportional and resulted in slower rates in the ratcheting progress over multiaxial stress cycles [37]. To study the influence of non-proportionality, complex loading paths, and loading steps on ratcheting response of materials, several ratcheting experiments have been conducted [37–54]. Hassan et al. [5,8,43] investigated the capability of kinematic hardening rules in ratcheting simulation of materials under multiaxial stress cycles and reported that the effect of non-proportionality was yet to be fully addressed. Jiang and Sehitoglu [47] examined ratcheting response of 1070 steel samples under uniaxial and multiaxial step-loading histories. They investigated ratcheting response of steel samples under uniaxial high–low and low–high step-loading histories as well

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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
$d\varepsilon^t_{ij}$	Incremental strain tensor
$d\sigma_{ij}$	Incremental stress tensor
E	Young's Modulus
f	Yield surface function
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 rule
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

as two-step axial–torsional loading paths. Haupt and Schinke [48] conducted two-step loading tests on austenitic AISI 316L (N) stainless steel samples at room temperature and discussed the influence of loading sequence on ratcheting response of steel samples. The impact of loading sequence, stress amplitude and mean stress on ratcheting response of SA333 C–Mn and 304LN steel alloys over steps of loading was examined by Paul et al. [49,50]. Kang et al. [27,39,51–54] investigated ratcheting response of 304 and 316 stainless steel alloys under uniaxial and multiaxial step-loading histories. Goodman [54] investigated the ratcheting response of SS316 steel samples under multi-step loading histories and discussed how influential the effect of mean stress magnitude on ratcheting response is while the applied stress amplitude is kept constant. On the other hand, Hassan and Kyriakides [4] discussed the ratcheting response of 1026 steel samples tested under multi-step loading with an increasing stress amplitude and a constant mean stress over loading steps. Ahmadzadeh–Varvani [35] evaluated ratcheting response of SS316L, SA333, SS316L (N) and 1070 steel alloys undergoing various uniaxial low–high, high–low, low–high–low and high–low–high loading sequences by means of the A–V hardening rule and discussed the influence of the prior load step for different loading sequences affecting the ratcheting progress in subsequent steps.

The present study intends to evaluate ratcheting response of 304 stainless steel samples under three-step multiaxial loading histories by means of the modified hardening rule as well as earlier well-known models of O–W and C–J–K as compared with experimentally obtained ratcheting data. The predicted ratcheting curves and generated strain paths based on the modified model closely agreed with experimentally obtained strain paths of SS304 steel samples over loading steps. In the modified hardening rule, terms holding unity vector $\bar{a}/|\bar{a}|$ and normal vector $\bar{n}$ are coupled to control ratcheting rate and direction over multiaxial stress cycles under non-proportional loading condition.

2. Framework of cyclic plasticity

The framework of cyclic plasticity is constituted through elements of strain increment, Hooke's law, yield function, flow rule, hardening rule and consistency condition. The von Mises criterion is given as

$$f(\bar{s},\bar{a},\sigma_y)=\frac{3}{2}(\bar{s}-\bar{a})\cdot(\bar{s}-\bar{a})-\sigma_y^2=0 \tag{1}$$

where $\bar{s}$ is the deviatoric stress tensor and defined as

$$\bar{s}=\bar{\sigma}-\frac{1}{3}(\bar{\sigma}\cdot\bar{I})\bar{I} \tag{2}$$

During loading, the size and shape of yield surface remain unchanged. The total strain increment is decomposed to the elastic and plastic strain components

$$d\bar{\varepsilon}=d\bar{\varepsilon}^e+d\bar{\varepsilon}^p \tag{3}$$

The elastic strain is determined by Hooke's law

$$\bar{\varepsilon}^e=\frac{\bar{\sigma}}{2G}-\frac{\upsilon}{E}(\bar{\sigma}\cdot\bar{I})\bar{I} \tag{4}$$

where terms $\bar{I}$ and $\bar{\sigma}$ correspond respectively to unity and stress vectors. The plastic strain increment is defined on the basis of employed flow rule as

$$d\bar{\varepsilon}^p=\frac{1}{H_p}(d\bar{s}\cdot\bar{n})\bar{n} \tag{5}$$

where the normal vector to yield surface is defined as

$$\bar{n}=\frac{\bar{s}-\bar{a}}{|\bar{s}-\bar{a}|} \tag{6}$$

Terms H_p and $d\bar{s}$ are the plastic modulus and the increment of deviatoric stress tensor, respectively. During an elastic–plastic deformation loading condition the consistency condition of yield surface needs to be satisfied. The consistency condition implies for the same projection of backstress and stress state increments on the unit exterior normal $\bar{n}$ during an elastic–plastic loading condition. 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 sections, brief descriptions of the O–W, C–J–K and modified A–V models are 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 is defined based on the superposition of M independent backstress