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Multiaxial life predictions in absence of any fatigue properties

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ABSTRACT

The aim of this study is to estimate fatigue life of steels and super alloys under multiaxial loading based on commonly available tensile properties. The state of loading for most components and structures is multiaxial resulting from multidirectional loading or stress concentrations. Multiaxial fatigue models have been developed to predict fatigue behavior under multiaxial loading. These models relate multiaxial stress/strain components to uniaxial fatigue properties in order to predict fatigue life. In this study, Muralidharan–Manson, Bäumel–Seeger, and Roessle–Fatemi prediction methods are employed to predict uniaxial fatigue properties based on simple tensile properties in the absence of any fatigue data. Appropriate multiaxial fatigue models representing the damage mechanism are then used along with the estimated uniaxial fatigue properties to predict fatigue lives under in-phase and out-of-phase multiaxial loading. Predictions are compared with experimental multiaxial data for sixteen different steels and super alloys from literature. Some approximation techniques to predict stress response for in-phase and out-of-phase loading based on simple tensile properties are also reviewed. Stress estimated based on these approximation techniques are then used in multiaxial fatigue life predictions and results are compared with experimental observations. It is concluded that fatigue life of steels and super alloys under multiaxial loading may be predicted reasonably well using appropriate damage models only requiring monotonic properties.

1. Introduction

Multiaxial states of loading are very typical in many industrial applications. The multiaxial stresses/strains in critical elements of components and structures can result from multidirectional loading, stress concentrations due to geometrical complexity, and residual stresses generated from manufacturing processes. Multiaxial loading can be categorized as in-phase (IP) and out-of-phase (OP) loading. For in-phase loading, the ratio of torsion to axial loading and principal directions remain fixed. However, under out-of-phase loading, principal directions and consequently maximum shear directions rotate in time.

Fatigue lives under out-of-phase loading are usually shorter than in-phase loading at the same equivalent strain level. Kanazawa et al. [1] related the shorter fatigue lives under out-of-phase (non-proportional) loading to the non-proportional cyclic hardening phenomenon. They [1] explained this additional non-proportional cyclic hardening phenomenon with the change in slip plane from one crystallographic slip system to another one resulting from the rotation of maximum shear plane under non-proportional loading. The interaction of active slip systems then may cause an additional hardening under non-proportional cyclic loading.

Multiaxial fatigue models can be used to relate multiaxial state of loading to uniaxial fatigue properties. Classical models, such as Maximum Principal Strain and von Mises, were first proposed in the early twentieth century as failure theories under static or monotonic loading. These hypotheses were later extended to cyclic loading and fatigue strength. For tensile failure mode materials, the Maximum Principal Strain model has been commonly used to predict fatigue life. The Maximum Principal Strain is related to fatigue properties and life as shown below:

$$\varepsilon_{1,\max} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \tag{1}$$

where E is modulus of elasticity, $2N_f$ is the number of reversals to failure, and σ_f', ε_f', b, c are the fatigue strength coefficient, fatigue ductility coefficient, fatigue strength exponent, and fatigue ductility exponent, respectively.

The von Mises equivalent strain is used for shear failure mode materials. The equivalent von Mises strain is calculated as:

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Nomenclature

b	axial fatigue strength exponent
c	axial fatigue ductility exponent
E	modulus of elasticity
FS	Fatemi–Socie
HB	Brinell Hardness
IP	in-phase
k	material constant in the FS parameter
K	strength coefficient
K'	cyclic strength coefficient
n	strain hardening exponent
n'	cyclic strain hardening exponent
$2N_f$	reversals to failure
OP	out-of-phase
SWT	Smith–Watson–Topper
α	non-proportional cyclic hardening coefficient
γ	shear strain
$\Delta\gamma_{\max}$	maximum shear strain range
$\Delta\gamma_{\max}/2$	maximum shear strain amplitude
$\Delta\gamma/2$	shear strain amplitude
$\Delta\bar{\varepsilon}$	equivalent strain range
$\Delta\bar{\varepsilon}_e$	equivalent elastic strain range
$\Delta\bar{\varepsilon}_p$	equivalent plastic strain range
$\Delta\varepsilon/2$	axial strain amplitude
$\Delta\bar{\varepsilon}/2$	equivalent strain amplitude
$\Delta\varepsilon_{1,\max}/2$	maximum principal strain amplitude
$\Delta\bar{\sigma}_{IP}$	equivalent in-phase stress range
$\Delta\bar{\sigma}_{OP}$	equivalent out-of-phase stress range
$\Delta\sigma/2$	axial stress amplitude
$\Delta\tau/2$	shear stress amplitude
ε	axial strain
ε_f	true fracture strain
$\varepsilon_{1,\max}$	maximum principal strain
$\bar{\varepsilon}_a$	equivalent strain amplitude
$\bar{\varepsilon}_e$	equivalent elastic strain
$\bar{\varepsilon}_p$	equivalent plastic strain
ε'_f	axial fatigue ductility coefficient
ψ	material constant in Bäumel–Seeger method
λ	shear to axial strain ratio
ν_e	elastic Poisson's ratio
ν_p	plastic Poisson's ratio
$\bar{\nu}$	equivalent Poisson's ratio
σ	normal stress
$\sigma_1^{\max}$	maximum normal stress on the maximum principal strain plane
$\sigma_n^{\max}$	maximum normal stress on the maximum shear strain plane
σ_u	ultimate strength
σ_y	yield strength
$\bar{\sigma}_{IP}$	in-phase equivalent stress
$\bar{\sigma}_{OP}$	90° out-of-phase equivalent stress
σ'_f	axial fatigue strength coefficient
τ	shear stress

$$\bar{\varepsilon}_a = \frac{1}{\sqrt{2}(1+\bar{\nu})}\sqrt{2\left(\frac{\Delta\varepsilon}{2}\right)^2(1+\bar{\nu})^2 + \frac{3}{2}\left(\frac{\Delta\gamma}{2}\right)^2} \tag{2}$$

where $\Delta\varepsilon/2$ is the axial strain amplitude, $\Delta\gamma/2$ is the shear strain amplitude, and $\bar{\nu}$ is the equivalent Poisson's ratio and can be calculated from Eq. (3):

$$\bar{\nu} = \frac{\nu_e\Delta\bar{\varepsilon}_e + \nu_p\Delta\bar{\varepsilon}_p}{\Delta\bar{\varepsilon}} \tag{3}$$

where $\bar{\varepsilon}_e$, $\bar{\varepsilon}_p$, and $\bar{\varepsilon}$ are equivalent elastic, plastic, and total strains and ν_e and ν_p are elastic and plastic Poisson's ratios. The von Mises equivalent strain and fatigue life are related through the following Coffin–Manson equation (i.e. Eq. (4)), and therefore, this equation can be used to calculate fatigue life based on the von Mises criterion, when equivalent strain is calculated from Eq. (2):

$$\bar{\varepsilon}_a = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c \tag{4}$$

However, these classical models may only work for proportional or in-phase loading. For the case of non-proportional or out-of-phase loadings, using classical models often leads to significant errors as these models do not consider the effects of load non-proportionality. Critical plane models which reflect the damage mechanism and predict the failure on the specific critical plane(s) within the material have been developed over the last few decades [2]. These models may be used for fatigue life estimations under both IP and OP loading and also for predicting the direction of crack initiation. Among all types of critical plane approaches, strain–stress-based models have the advantage of reflecting the constitutive behavior of material such as non-proportional cyclic hardening. These models include both a strain component as the driving parameter and a secondary stress component taking into account the cyclic hardening due to non-proportionality of loading as well as mean and residual stresses. Smith–Watson–Topper (SWT) [3] and Fatemi–Socie (FS) [4] damage parameters are two examples of strain–stress-based critical plane approaches for tensile and shear failure mode materials, respectively.

The Smith–Watson–Topper (SWT) critical plane model for tensile failure mode materials considers the maximum principal strain amplitude, $\Delta\varepsilon_{1,\max}/2$, as the primary parameter driving the crack and the maximum normal stress on the principal plane, $\sigma_1^{\max}$, as the secondary parameter opening the crack and expediting the failure process if tensile, as presented below:

$$\sigma_1^{\max}\frac{\Delta\varepsilon_{1,\max}}{2} = \frac{\sigma_f'^2}{E}(2N_f)^{2b} + \sigma'_f\varepsilon'_f(2N_f)^{b+c} \tag{5}$$

The Fatemi–Socie (FS) critical plane model for shear failure mode materials is expressed as a function of maximum shear strain amplitude, $\Delta\gamma_{\max}/2$, as the primary parameter driving the crack and maximum normal stress acting on the maximum shear strain plane, $\sigma_n^{\max}$, as the secondary parameter, as presented by Eq. (6). The maximum normal stress on the maximum shear plane opens the crack and expedites the failure process if tensile or closes the crack and retards the failure process if compressive. The uniaxial form of the FS equation is given as:

$$\frac{\Delta\gamma_{\max}}{2}\left[1 + k\left(\frac{\sigma_n^{\max}}{\sigma_y}\right)\right] = \left[(1+\nu_e)\frac{\sigma'_f}{E}(2N_f)^b + (1+\nu_p)\varepsilon'_f(2N_f)^c\right]\left[1 + k\frac{\sigma'_f}{2\sigma_y}(2N_f)^b\right] \tag{6}$$

where σ_y is the material monotonic yield strength, and k is a material constant found by fitting fatigue data from uniaxial tests to fatigue data from torsion tests.

Fatigue data are not always available and generating fatigue properties is an expensive process. Furthermore, a slight change in material chemical composition or any surface enhancements such as shot peening or hardening may greatly affect the fatigue behavior. Therefore, developing predictive techniques for fatigue