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Multiaxial fatigue damage parameter and life prediction for medium-carbon steel based on the critical plane approach

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Abstract

The tension–torsion fatigue characteristics were investigated under proportional and non-proportional loading in this paper. The fatigue cracks on the surface of multiaxial fatigue specimens were observed and analyzed by a scan electron microscope. On the basis of the investigation on the Kindil–Brown–Miller and Fatemi–Socie's critical plane approaches, a shear strain based multiaxial fatigue damage parameter was proposed by von Mises criterion based on combining the maximum shear strain and the normal strain excursion between adjacent turning points of the maximum shear strain on the critical plane. The proposed multiaxial fatigue damage parameter does not include the weight constants. According to the proposed multiaxial fatigue damage parameter, the multiaxial fatigue life prediction model was established with the Coffin–Manson equation, which is used to predict the multiaxial fatigue life of medium-carbon steel. The results showed that the proposed multiaxial fatigue damage parameter could be used under either multiaxial proportional or non-proportional loading.

Keywords: Multiaxial fatigue; Critical plane approach; Constant amplitude loading; Life prediction

1. Introduction

The engineering components of machines in service are frequently subjected to the multiaxial cyclic loading, which can result in failure due to the fatigue damage. In general, the multiaxial fatigue life can be predicted by von Mises equivalent stress or strain criterion. However, under out-of-phase or non-proportional loading, the principal axes of stress and strain rotate during cyclic loading, causing additional cyclic hardening of the material, which results in more fatigue damage [1]. Some multiaxial fatigue models have been proposed for the prediction of multiaxial fatigue life, such as Findley [2] proposed a multiaxial fatigue model based on the stress components by the linear relationship between the maximum normal stress and the shear amplitude. Brown and Miller [3] presented the critical plane approach, and a similar approach was also given by Lohr and Ellison [4].

At present, the critical plane approach is widely accepted for the multiaxial fatigue life prediction, but it is required to determine the maximum damage plane and the stress or strain on the plane. The relationship between the maximum shear strain and normal strain amplitude perpendicular to the maximum shear strain plane and the fatigue life is usually proposed as

$$\Delta\gamma_{\max}/2 + f'(\Delta\varepsilon_n/2) = f(N_i), \quad (1)$$

where f' is a function with the normal strain amplitude, $f(N_i)$ is usually the right term of the Coffin–Manson equation.

The multiaxial fatigue damage parameter proposed by Kindil et al. [5] is

$$\Delta\gamma_{\max}/2 + S\varepsilon_n = f(N_i), \quad (2)$$

where, $\Delta\gamma_{\max}/2$, ε_n are the maximum shear strain amplitude and the normal strain amplitude on the maximum shear plane, respectively. S is a constant.

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Nomenclature

$\Delta\gamma_{max}$	maximum shear strain range	ε_n^*	normal strain excursion between adjacent turning points of the maximum strain on the critical plane
$\Delta\varepsilon$	applied axial strain range	σ'_f	fatigue strength coefficient
$\Delta\gamma$	applied shear strain range	b	fatigue strength exponent
λ	ratio of torsional and axial strain amplitudes	ε'_f	fatigue ductility coefficient
R_ε	axial strain ratio	c	fatigue strength exponent
R_γ	shear strain ratio	τ'_f	pure torsion fatigue strength coefficient
φ	phase angle between the axial and torsional strain amplitudes.	b'	pure torsion fatigue strength exponent
ε_n	normal strain amplitude on the maximum shear plane	γ'_f	pure torsion fatigue ductility coefficient
θ_c	orientation angle of the maximum shear plane	c'	pure torsion fatigue strength exponent
		N_f	number of cycles to fatigue failure

The multiaxial fatigue damage equation proposed by Fatemi and Socie's parameter is the following form [6]:

$$\Delta\gamma_{max}/2(1 + k\sigma_n^{max}/\sigma_y) = f(N_i), \tag{3}$$

where, σ_n^{max} is the maximum normal stress on the critical plane, σ_y is the yield stress, and k is a constant. McDiarmid [7] also gave an approach based on the shear and normal stresses on the critical plane, which used the shear and normal stress or strain to form the fatigue damage parameter.

The above approaches have been widely accepted to predict the multiaxial fatigue life. However, some damage parameters in these approaches usually include the weight constants that tend to increase as fatigue life increases [8]. Sometimes it may be difficult to correlate the data for a wide variety of materials.

The objective of this paper is to propose a shear strain based multiaxial damage parameter to predict the multiaxial fatigue life of medium-carbon steel based on the critical plane approach. The proposed fatigue damage parameter does not include the weight constant, which can be used under either multiaxial proportional loading or non-proportional loading.

2. Multiaxial fatigue experiment

Hot-rolled 45 steel (60 mm diameter) in the normalized condition was used in this investigation. The tensile properties of the material at room temperature were yield strength 370 MPa, ultimate tensile strength 610 MPa, and elongation 26.36%.

All tests were carried out on a MTS809-250 KN servo-hydrulic fatigue test facility that was automated for test control and data acquisition. Thin-walled tubular specimens with a uniform gouge length of 50 mm, an outside diameter of 25 mm, and an inside diameter of 21 mm were used in this investigation. The strain was measured by MTS632.68C-01 tension–torsion extensometer. All tests were conducted under total strain amplitude control using a sinusoidal waveform at a constant cyclic frequency of 0.08 Hz.

The equivalent stress and strain are defined as follows:

$$\sigma_{eq} = \left(\sigma^2 + 3\tau^2\right)^{1/2}, \tag{4}$$

$$\varepsilon_{eq} = \left(\varepsilon^2 + \gamma^2/3\right)^{1/2}. \tag{5}$$

The applied strains are sinusoidal:

$$\varepsilon = \varepsilon_a \sin \omega t \tag{6}$$

$$\gamma = \lambda\varepsilon_a \sin(\omega t - \varphi), \tag{7}$$

where $\lambda = \gamma_a/\varepsilon_a$, $\varepsilon_a = \Delta\varepsilon/2$, $\gamma_a = \Delta\gamma/2$, φ is the phase angle between the axial and torsional strains. $\Delta\varepsilon$ and $\Delta\gamma$ are the applied axial and torsional strain ranges, respectively.

First, three specimens were used for the tension–torsion cyclic stress–strain response tests under proportional, 45° elliptic non-proportional, and circle non-proportional loadings, respectively. These tests were fully-reversed cyclic loading. The total strain amplitude control was achieved using three specimens for three loading paths at five levels of strain loading, that is, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%. The cyclic loading for each strain level continued about 40 cycles, which makes the material reach the cyclic stabilization. The stress–strain hysteresis loops at cyclic stabilization were recorded on an X–Y recorder equipped with a pen plotter. The loading parameters are shown in Table 1. Next, the strain-controlled multiaxial low-cycle fatigue tests were carried out at room temperature under sinusoidal strain waveform in air environment. The strain ratio was varied from zero to infinity. The selected strain paths for multiaxial fatigue tests are shown in Fig. 1, and the controlled loading parameters are listed in Table 2.

3. Analysis of experimental results

3.1. Behavior of cyclic stress–strain response under multiaxial loading

During the constant amplitude strain-controlled testing process, after the initial cyclic hardening or softening was completed, the cyclic stress–strain behavior should be stable. Specimen A was subjected to proportional loadings