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Multiaxial high-cycle fatigue criterion for notches and superficial small holes from considerations of crack initiation and non-propagation

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ABSTRACT

A new criterion is proposed for evaluating the multiaxial high-cycle fatigue limit of components with notches and superficial small holes. Two parameters are specified: (1) one governing crack initiation and (2) the other governing initial crack growth. The new criterion is based on the multiaxial fatigue criterion for smooth components previously proposed by the authors. The accuracies of the proposed and conventional criteria are evaluated using experimentally determined fatigue limit data of notches and superficial small holes under combined bending and torsion stresses and combined axial and torsion stresses. The error of the proposed criterion is approximately 10%.

1. Introduction

Mechanical components with complex shapes are frequently subjected to multiaxial stresses. The fatigue fracture of such components is caused by stress concentration at the notch. Therefore, in proper fatigue design, the notch fatigue limit under multiaxial stresses must be evaluated.

The uniaxial fatigue limits of notches are conventionally predicted by the Peterson evaluation method and the Siebel evaluation method [1,2]. For each material, the Peterson's method experimentally evaluates the correlation between the notch sensitivity and the notch radius, while the Siebel's method experimentally evaluates the correlation between the ratio of the elastic stress concentration factor to the notch factor and the stress gradient at the notch root.

The multiaxial fatigue in smooth components is traditionally evaluated by the critical plane approach and the stress invariant approach. The former approach uses the maximum shear stress and the normal stress acting on the critical plane [3–8], while the latter uses the equivalent shear stress amplitude and hydrostatic stress [9–13].

Forsyth [14] divided the fatigue fracture mechanism into the initiation of a crack from a surface (Stage I of the process) and crack growth (Stage II). Under cyclic stress, a slip band resulting from shear stress develops on a metal surface during Stage I. This band arises from the generation of microscopic irregularities, such as intrusions and extrusions. A crack formed in this way grows inward from the surface under the cyclic shear stress. Despite the crack growth direction in Stage I, the crack grows perpendicularly to the direction of the maximum principal stress in Stage II.

In a previous report, we proposed a method for evaluating multiaxial fatigue limits of smooth components [15]. This method requires the equivalent shear stress amplitude that governs crack initiation and a parameter S_{max} that determines the initial crack growth. The method accounts for phase difference, mean stress and the ratios in combinations of stresses and was verified using previously reported fatigue limit data. The proposed method proved more accurate than conventional stress invariant approaches, namely, the Sines criterion, the Crossland criterion and the Li criterion.

In this study, the same mechanism is assumed to cause fatigue fractures in notched components. The fatigue limit is regarded as the stress condition under which a crack initiated in Stage I terminates in Stage II. The multiaxial fatigue criterion for smooth components proposed by the authors is extended to a multiaxial fatigue criterion for notched components. This paper first introduces conventional multiaxial high-cycle fatigue criteria and the previously proposed criterion for smooth components. It then describes conventional multiaxial fatigue criteria and the proposed criterion for notched components in Section 3. In Section 4, the accuracies of the conventional and proposed notch criteria are verified from previously published fatigue limit data [16–20] under combined loadings of circumferential notches, circular holes and

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Nomenclature

$\sqrt{J_{2,a}}$	equivalent shear stress amplitude
$\sigma_{\mathrm{H,max}}$	maximum hydrostatic stress
s_{ij} $(i, j = x, y, z)$	deviatoric stress component
α, β	material parameter for criterion
R_a, R_b	major and minor radius of ellipse, respectively
$\Delta K_{\max}$	maximum range of stress intensity factor
K_t	elastic stress concentration factor
K_f	notch factor
K_σ	plastic–elastic stress concentration factor
K_ε	plastic–elastic strain concentration factor
ε_e	elastic strain
ε_p	plastic strain
E	Young's modulus
I	error index
σ_n	nominal stress
σ_T	true fracture strength
σ_u	ultimate tensile strength
σ_y	yield stress
σ_{w0}	fully reversed bending fatigue limit for smooth specimen
τ_{w0}	fully reversed torsional fatigue limit for smooth specimen
$\sigma_{w0,ax.}$	fully reversed axial fatigue limit for smooth specimen
σ_{wN}	fully reversed bending notched fatigue limit
τ_{wN}	fully reversed torsional notched fatigue limit
$\sigma_{wN,ax.}$	fully reversed axial notched fatigue limit
σ_{w1}	fully reversed bending notched fatigue limit with minimum non-propagation crack
τ_{w1}	fully reversed torsional notched fatigue limit with minimum non-propagation crack
σ_{w2}	fully reversed bending notched fatigue limit with maximum non-propagation crack
τ_{w2}	fully reversed torsional notched fatigue limit with maximum non-propagation crack
$\theta_{\sigma\tau}$	phase difference between bending and torsion stresses
$\theta_{\sigma ax.\tau}$	phase difference between axial and torsion stresses
R	load ratio

Subscripts

a	amplitude
m	mean
max	maximum
ax.	axial mode
bend.	bending mode
tor.	torsional mode
C	Crossland criterion
L	Li criterion
P	Authors' proposed criterion

superficial small holes. Non-propagating crack behavior at the notch root and the practicality of the stress correction in the proposed criterion are discussed in Section 5. The paper concludes with Section 6.

This study does not attempt to predict the notch factors. Therefore, the notch factors used in this paper are strictly derived from experiments.

2. Multiaxial fatigue criteria for smooth components

This section describes conventional multiaxial fatigue criteria (the Crossland and Li criteria) and the proposed criterion for smooth components [10,13]. The Crossland criterion is a typical stress invariant approach. The Li criterion has been improved to evaluate the effect of the phase difference in combined loading.

2.1. Crossland criterion

The Crossland criterion requires the equivalent shear stress amplitude $\sqrt{J_{2,a}}$, which is the square root of the second deviatoric stress invariant and the maximum hydrostatic stress $\sigma_{\mathrm{H,max}}$ [10]. The $\sqrt{J_{2,a}}$ is expressed in terms of five stresses, such as

$$\sqrt{J_{2,a}} = \sqrt{S_1^2 + S_2^2 + S_3^2 + S_4^2 + S_5^2}, \tag{1}$$

where $S_1 = \dfrac{\sqrt{3}}{2} s_{xx}, \quad S_2 = \dfrac{1}{2}(s_{yy} - s_{zz}), \quad S_3 = s_{xy}, \quad S_4 = s_{xz}, \quad S_5 = s_{yz}$.

Here, s_{xx}, s_{yy}, s_{zz}, s_{xy}, s_{yz} and s_{xz} are the deviatoric stresses. Given the surface stress, the path of the equivalent shear stress can be drawn in three-dimensional Euclidean space. The $\sqrt{J_{2,a}}$ defines the radius of the minimum circle circumscribed on the stress pass, calculated by sequential linear programming [13].

The criterion equation is given by

$$\sqrt{J_{2,a}} + \alpha_C \sigma_{\mathrm{H,max}} = \beta_C, \tag{2}$$

where $\alpha_C = \dfrac{3\tau_{w0}}{\sigma_{w0}} - \sqrt{3}, \ \beta_C = \tau_{w0}$

The criterion requires two material properties: the fully reversed bending fatigue limit σ_{w0} and the fully reversed torsion fatigue limit τ_{w0}. The Crossland criterion is illustrated in Fig. 1.

2.2. Li criterion

The mathematical constructs of the Li and Crossland criteria are identical [13], but the Li criterion assumes a different definition of $\sqrt{J_{2,a}}$. The $\sqrt{J_{2,a}}$ in the Li criterion is expressed as $\sqrt{(R_a^2 + R_b^2)}$, where R_a and R_b denote the major radius and minor radius, respectively, of an ellipse circumscribed on the stress path. This so-called minimum circumscribed ellipse (MCE) approach considers the effect of phase difference. Fig. 2 shows a schematic of the stress paths.

2.3. Proposed criterion for smooth components

The two parameters in the proposed criterion govern crack initiation and initial crack growth. The proposed criterion for smooth components is detailed in our previous report [15].

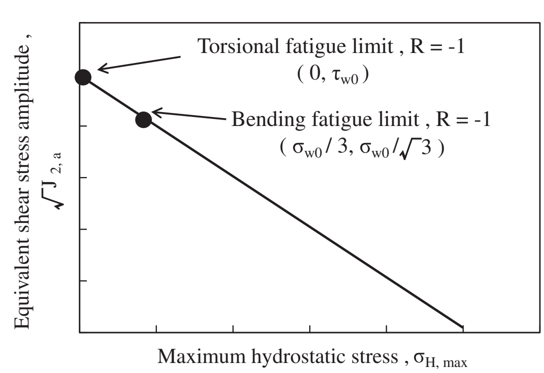

Fig. 1. Crossland criterion.