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A multiaxial fatigue criterion for various metallic materials under proportional and nonproportional loading

Ying-Yu Wang*, Wei-Xing Yao

Department of Aircraft Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

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Abstract

Proportional and nonproportional tension–torsion fatigue tests were conducted on LY12CZ aluminum alloy. Two types of tubular specimens were used, one is smooth and the other is notched. The experimental data are analyzed. A new critical plane criterion including the strain and stress parameters is proposed. The capability of fatigue life prediction for the proposed fatigue damage model is checked against the experimental data of LY12CZ aluminum alloy and two other metals under proportional and nonproportional loading, and the predicted results are compared with results from common multiaxial fatigue model. It is demonstrated that the proposed criterion gives better satisfactory results for all the three checked materials.

Keywords: Multiaxial fatigue; Fatigue criteria; Critical plane approach; Nonproportional loading

1. Introduction

Many engineering components usually undergo complex multiaxial loadings, which lead to changing of the principle stresses and strains directions during a cycle of loading. The additional hardening of material, which is caused by the rotation of the principle stress and strain axes, is considered to have tight relation to the reduction of fatigue life under nonproportional loading compared with that under proportional loading [1–4]. Although many multiaxial fatigue criteria suitable to different materials and different loading conditions have been proposed, those capabilities to correlate the experimental fatigue life under multiaxial loading do not reach a satisfactory level. Reviews of available multiaxial fatigue life prediction methods are presented by Garud [5], Brown and Miller [6], You and Lee [7], Papadopoulos [8], Macha and Sonsino [9], Wang and Yao [10]. Fatigue life prediction approaches using the concept of a critical plane have been found very effective because the critical plane concept is based on the physical observations that cracks initiate and grow on preferred planes. According to the parameter used in the fatigue criteria, the critical plane approaches can be classified into three categories, namely stress critical plane criteria [11–15], strain critical plane criteria [16–21] and energy critical plane criteria [22–25]. However, the critical plane approaches have a shortcoming due to the fact that the critical plane does not always coincide with the plane where the fatigue damage parameter takes its maximum value [26–28]. Successful models should be able to predict both the fatigue life and the dominant failure plane(s) [29].

In the present study, a series of proportional and nonproportional tension–torsion fatigue tests were conducted on LY12CZ aluminum alloy. Two types of tubular specimens were used, one is smooth and the other is notched. The objective of the fatigue tests on the notched specimen is to study fatigue crack nucleation angle under multiaxial loading. A multiaxial fatigue parameter based on the critical plane concept is proposed. Two methods to define the critical plane (one is the maximum shear strain range plane and the other is the maximum fatigue damage plane) are compared with the statistical experimental results of the crack nucleation angle. The predictive capabilities of the proposed parameter and one popular multiaxial fatigue model proposed by Kandil, Brown and Miller [17] are

* Corresponding author. Tel.: +86 25 84892177; fax: +86 25 84891422.
E-mail address: yukiiwyy@hotmail.com (Y.-Y. Wang).

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Nomenclature

$\Delta\varepsilon_n$	normal strain range on the critical plane	n	strain hardening exponent
$\Delta\gamma$	shear strain range on the critical plane	θ	crack nucleation angle
$\Delta\gamma_{max}$	maximum shear strain range	D	damage parameter
σ_n	normal stress amplitude on the critical plane	σ_f'	axial fatigue strength coefficient
E	Young's modulus	b	axial fatigue strength exponent and
σ_y	yield stress (0.2%)	ε_f'	axial fatigue ductility coefficient
σ_u	ultimate strength	c	axial fatigue ductility exponent
σ_f	true fracture strength	N_f	fatigue life
ε_f	true fracture strain	N_{50}	fatigue life at survival probability 50%
K	strength coefficient		

checked against the experimental data of LY12CZ aluminum alloy, and some other experimental data on 1045 steel [30] and 6061 aluminum alloy [31] under multiaxial loading are also compared.

2. Experiment

2.1. Material and specimen

The material tested was a common aeronautic material, LY12CZ aluminum alloy. The material has the following chemical compositions (wt%): Cu4.34; Mg1.48; Mn0.77; Fe0.29; Si < 0.15; Zn < 0.1; Ni < 0.05 and its mechanical and cyclic properties are shown in Tables 1 and 2, respectively. The mechanical and cyclic properties of two other metals, which will be employed to check the proposed models for fatigue life prediction, are also listed in Tables 1 and 2, respectively. Two types of tubular specimens were used, the first one is a thin-walled tubular specimen (in Fig. 1) while the other is a notched thin-walled tubular specimen (in Fig. 2), the notch is a transverse circular hole with 2 mm diameter on semi-circle of the tubular specimen.

2.2. Experimental procedure and results

Stress controlled tension–torsion biaxial fatigue tests were carried out on a servo-hydraulic MTS Model 858 axial-torsion testing system. The experiments were conducted at room temperature. A fully reversed sinusoidal stress wave was used (i.e. the stress ratio is equal to −1.0).

2.2.1. Experiment of the thin-walled tubular specimen

The stress paths employed in this study were: (a) in-phase, (b) 45° out-of-phase, (c) 90° out-of-phase loading. Three maximum Mises' equivalent stress amplitudes for each stress path were chosen, that is 350, 300 and 250 MPa, respectively. The testing frequencies were 10 Hz. Five specimens were tested for each loading condition. The failure was defined as the first observation of a surface crack 1.0 mm long. The experimental results are summarized in Table 3.

2.2.2. Experiment of the notched tubular specimen

The stress paths employed on the notched tubular specimens were: (a) in-phase, (b) 45° out-of-phase and (c) 90° out-of-phase loading. The maximum Mises' equivalent stress amplitude used in each test was 161 MPa. The testing

Table 1
Mechanical properties of LY12CZ, 1045 steel and 6061 aluminum alloy

Material	E (GPa)	σ_y (Mpa)	σ_u (MPa)	ν	σ_f (MPa)	ε_f	K (MPa)	n
LY12CZ	73	400	545	0.33	643	0.18	850	0.158
1045HR	202	380	621	0.29	985	0.71	1185	0.23
6061Al	80	337		0.32				

Table 2
Material cyclic properties

Material	σ_f' (MPa)	b	ε_f'	c	K (MPa)	n'
LY12CZ	724	−0.063	0.137	−0.654	870	0.097
1045HR[a]	948	−0.092	0.260	−0.445	1258	0.208
6061Al[b]	528	−0.089	0.225	−0.629	470	0.11

[a] Fatigue properties are given by referenced papers.
[b] Fatigue properties are calculated from test data.