Engineering Fracture Mechanics 136 (2015) 115–130

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Study of crack orientation and fatigue life prediction in biaxial fatigue with critical plane models

P. Lopez-Crespo [a,*], B. Moreno [a], A. Lopez-Moreno [b], J. Zapatero [a]

[a] *Department of Civil and Materials Engineering, University of Malaga, C/Dr. Ortiz Ramos s/n, 29071 Malaga, Spain*
[b] *Department of Materials Science and Metallurgy Engineering, University of Jaen, Campus Las Lagunillas, 23071 Jaen, Spain*

ARTICLE INFO

Article history:
Received 9 April 2014
Received in revised form 23 January 2015
Accepted 24 January 2015
Available online 30 January 2015

Keywords:
Fracture plane
Short crack
Long crack
Critical fracture plane
Fatigue life
Mixed mode fracture
Biaxial fatigue
St52-3N steel

ABSTRACT

The crack initiation and propagation behaviour of St52-3N steel is investigated under biaxial conditions. Short crack behaviour is studied and pearlite bands are found to modify the crack growth rate. The behaviour under proportional and non-proportional (90°) loading is studied with different critical plane models; Wang–Brown, Fatemi–Socie, Smith–Watson–Topper, Liu I and Liu II. Smith–Watson–Topper and Liu I are found to best predict the crack orientation under proportional loading and Fatemi–Socie and Liu II under non-proportional loading. The best predictions in terms of fatigue life are obtained by Fatemi–Socie, both under proportional and non-proportional loads.

1. Introduction

The majority of mechanical components experience multiaxial cyclic loading conditions. As a consequence two or three principal stresses and strains change in time, both in magnitude and direction. A number of theories have been proposed to estimate fatigue life under such complex conditions [1–4]. Of these theories, critical plane approaches were found to be very effective because they are based on the fracture mode or the initiation mechanism of cracks. They are founded on the physical observations that cracks initiate and grow on preferred planes. Critical plane approaches proved to be very successful in a wide range of applications and materials, including high strength 42CrMo steel [5], variable amplitude on a car component 1045 steel [6], S45C steel under variable amplitude loading [7], SNCM630 steel [8], 1045HR and 304 stainless steels [9]. Moreover critical plane approaches can predict not only the fatigue life under multiaxial loading, but also the cracking orientation. This latter element is of key importance since it influences, together with the geometric discontinuities and the multiaxial loading, the crack path during the propagation stage. The crack path in critical components can determine whether failure is catastrophic or not. In addition, accurate information about cracking direction is very helpful for selecting the most convenient non-destructive testing procedures. Nevertheless poor agreement is often observed between theoretically predicted and experimental tests [10]. As a consequence, since 2003 a series of international conferences have been devoted specifically to the path taken by cracks [11]. Even though critical plane approaches are able to provide information about fatigue lives and crack orientation, most works focus on fatigue life, with little attention paid to cracking orientation

* Corresponding author. Tel.: +34 951 952 308.
E-mail address: plopezcrespo@uma.es (P. Lopez-Crespo).

http://dx.doi.org/10.1016/j.engfracmech.2015.01.020
0013-7944/

Nomenclature

b	fatigue strength exponent
b_γ	fatigue strength exponent
c	fatigue ductility exponent
c_γ	fatigue ductility exponent
da/dN	crack growth rate
k	parameter represents the influence of the normal stress in Fatemi–Socie model
K'	cyclic strength coefficient
K'_γ	cyclic strength coefficient
n'	cyclic hardening exponent
n'_γ	cyclic hardening exponent
N_f	fatigue life, number of cycles
S	sensitivity factor for Brown–Miller model
γ_a	angular strain amplitude
γ'_f	fatigue ductility coefficient
$\Delta\gamma_{\max}/2$	maximum angular strain amplitude
$\Delta\varepsilon_n$	range of normal strain acting on the plane subjected to $\Delta\gamma_{\max}/2$
ΔW_{I}	axial work
ΔW_{II}	shear work
ε_a	axial strain amplitude
$\varepsilon_{\mathrm{eq}}$	von Mises equivalent strain
ε'_f	fatigue ductility coefficient
θ	angle between longitudinal direction of the specimen and the normal direction
ν_e	Poisson's ration in elastic deformation
ν_p	Poisson's ration in plastic deformation
σ_a	axial stress amplitude
σ_{cr}	critical buckling stress
$\sigma_{n,\max}$	maximum normal stress acting on the plane subjected to $\Delta\gamma_{\max}/2$
σ_x	normal stress
σ_y	yield strength
σ'_y	cyclic yield strength
σ'_f	fatigue strength coefficient
σ_u	ultimate tensile stress
τ_a	angular stress amplitude
τ_{xy}	torsional stress
τ'_y	cyclic yield strength
τ'_f	fatigue strength coefficient

[2,5–8,12,13]. Among the few works that have paid attention to crack orientation, Reis and co-authors used critical plane models to predict the crack orientation during early crack growth [14] and to predict fatigue life [15] for a wide range of axial/torsional loading paths. Other researchers employed an innovative approach by combining principal stress field and finite element method to predict the crack orientation under proportional [16] and both proportional and non-proportional loading [17]. As a consequence, one of the key aims of this work is to study the crack orientation under different load combinations.

There are a number of issues on multiaxial fatigue in which researchers do not completely agree [18]. For example, one of the most popular criterion [19] was found both to overestimate [20,21] and underestimate [8] fatigue life. Accordingly a comparative study of five widely used critical plane criteria (Wang–Brown [19], Fatemi–Socie [22] and Smith–Watson–Topper [23], Liu I and Liu II [24]) is shown here.

Biaxial experimental tests are difficult, expensive and time-consuming, hence the amount of biaxial data available in the literature is not as large as for uniaxial fatigue [9,25]. The current work aims to characterise the fatigue behaviour under biaxial conditions both during initiation and propagation stages. Since both stages depend on very different mechanisms [26,27], different methodologies will be used to study them. First, a methodology for characterising the crack growth of short fatigue cracks under biaxial loading is presented. Then a series of biaxial tests conducted to evaluate in-phase and out-of-phase conditions are described. Detailed observations on the cracking orientation are made for the initiation and propagation stages. Comparison between several critical plane theories is performed both in terms of fatigue life and crack orientation. Each section includes a discussion of the results shown in that specific section. An overall short discussion is included at the end. Practical issues often neglected in publications, such as how and where the orientation is measured and its length-scale are also discussed.