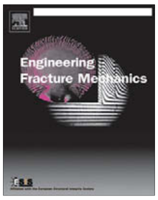
Engineering Fracture Mechanics 77 (2010) 1400–1416

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



Application of a modified Wheeler model to predict fatigue crack growth in Fibre Metal Laminates under variable amplitude loading

S.U. Khan *, R.C. Alderliesten, C.D. Rans, R. Benedictus

Aerospace Materials and Structures, Faculty of Aerospace Engineering, Delft University of Technology, P.O. Box 5058, 2600 GB Delft, The Netherlands

ARTICLE INFO

Article history:
Received 1 July 2009
Received in revised form 22 March 2010
Accepted 31 March 2010
Available online 4 April 2010

Keywords:
Fibre Metal Laminates
Effective stress intensity factor
Fatigue crack growth
Spectrum loading
Damage tolerance

ABSTRACT

This paper presents the investigation regarding fatigue crack growth prediction in Fibre Metal Laminates under variable amplitude fatigue loading. A recently developed constant amplitude analytical prediction model for Fibre Metal Laminates has been extended to predict fatigue crack growth under variable amplitude loading using the modified Wheeler model based on the Irwin crack-tip plasticity correction and effective stress intensity factor range (ΔK_{eff}). The fatigue crack growth predictions made with this model have been compared with crack growth tests on GLARE center-cracked tension specimens under selective variable amplitude loading as well as flight simulation loading. The accuracy of the model is discussed in comparison with the experimental fatigue crack growth data.

1. Introduction

Fatigue is one of the major problems faced by metallic structures and components while in service. In addition, most of the structures in real life are loaded under variable amplitude (*VA*) loading. Due to this fact, it becomes necessary to study the fatigue crack growth phenomenon under *VA* loading. The main difference between constant amplitude (*CA*) and *VA* loading is the existence of interaction phenomena related to *VA* loading. Crack growth retardation [1] due to overloads and crack growth acceleration [2] due to underloads are the most commonly observed interaction effects. In this paper, only interaction effects resulting from overloads will be considered, as large compressive underloads are not a common feature in the load spectra of fatigue critical components. Many investigations have been performed to understand the fatigue behaviour of different materials under *VA* loadings. This resulted in the development of a number of prediction models ranging from simple non-interaction models to more advance interaction models [3].

The retardation effects on crack growth resulting from a single overload cycle is illustrated in Fig. 1. During the overload cycle, yielding of the material near the crack-tip occurs, creating a large plastic zone [4–10]. Due to the presence of this plastic zone in front of the crack-tip, surrounded by an elastically deformed region, the crack-tip experiences a squeezing effect, which results in the development of residual compressive stresses in the vicinity of the crack-tip. The compressive stress field reduces the available crack-tip driving force and causes a significant reduction in fatigue crack growth rate [5,7,11]. The crack retardation zone, i.e. the crack extent over which retardation of crack growth is experienced, may be characterized by parameters, a_D (overload affected total crack length) and N_D (delay cycles), and is schematically represented in Fig. 1. After the crack has grown beyond this region, the crack growth rate returns to its original rate in the absence of other retardation effects.

---

* Corresponding author. Tel.: +31 (0) 152 786 279; fax: +31 (0) 152 781 151.
E-mail address: S.U.Khan@tudelft.nl (S.U. Khan).

0013-7944/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engfracmech.2010.03.041

Nomenclature

$\frac{da}{dN}$	crack growth rate (mm/cycle)
$\frac{db}{dN}$	delamination growth rate (mm/cycle)
R	stress ratio (–)
a	crack length (mm)
N	number of cycles (–)
r	plastic zone size (mm)
C_d,n_d	Paris constants for delamination relation (–)
C_P	Wheeler constant (–)
m	Wheeler coefficient for calculating C_P (–)
$G_{d,\max}$,$G_{d,\min}$	energy release rate (maximum, minimum) (MPa mm)
C_{cg},n_{cg}	Paris constants for crack growth relation (–)
K	stress intensity factor (Nm m$^{-3/2}$)
ε	strain (–)
S	stress (MPa)
$\varepsilon_{0.2}$	plastic strain (–)
v	crack-tip opening (mm)
δ	displacement (mm)

Indices

OL	overload (–)
TR	transition (–)
D	delayed (–)
y	Irwin plastic zone size (–)
p	corrected plastic zone size (–)
eff	effective (–)
br	bridging (–)
f	fibre related (–)
pp	prepreg related (–)
∞	far-field (–)

Abbreviation

FMLs	Fibre Metal Laminates (–)
VA	variable amplitude (–)
CA	constant amplitude (–)

Recently, a new aerospace material concept known as Fibre Metal Laminates (*FMLs*), has been developed as a damage tolerant replacement for monolithic aluminum alloys in aircraft structures. *FMLs* consist of alternate layers of uni-directional impregnated fiber lamina and thin metallic sheets adhesively bonded together. This hybrid material results in a combination of the favourable properties of its individual constituents, particularly with regards to damage tolerance and impact resistance.

One main advantage of *FMLs* is the slow and almost constant rate of crack growth under constant amplitude (*CA*) fatigue loading [12,13]. This property is related to the load bridging behaviour of the intact fibre layers between the cracked metallic layers. This bridging effect reduces the effective stress intensity factor in the cracked metallic layers, resulting in a smaller crack-tip plastic zone, and thus smaller interaction effects under variable amplitude (*VA*) loading. The presence of small interaction effects in *FMLs* has been proven in a comparative study performed to quantitatively investigate these interaction effects [14]. Similar type of selective *VA* load sequences have been applied to three types of materials i.e., FMLs, monolithic metal and metal laminates. Limited retardation effects were observed in FMLs due to small crack-tip plastic zones in comparison with other two type of materials under similar load spectra.

As far as acceleration effects are concerned, Plokker et al. [15] have reported the absence of crack growth acceleration effects in *FMLs* under different underloads and over/under load combinations and highlighted the presence, although to a lesser degree compared to monolithic metals, of crack growth retardation in *FMLs*. Due to this limited retardation, fatigue crack growth predictions under *VA* based on linear damage accumulation (considering a simple non-interaction model [15–17]), correlate well with experimental data obtained for load spectra with minor variations. However, a mismatch is observed in case of spectra where load variations are more distinct.

This raises the question whether a simple interaction model would be sufficient to describe the retardation effects during the large and distinct load sequences occurring in these load spectra. To answer this question, the Wheeler crack growth prediction model [18], being one of the simplest and most widely employed [19–33] models to quantify the fatigue crack growth retardation under selective *VA* loadings, has been selected for fatigue crack growth prediction in *FMLs*. For monolithic