International Journal of Fatigue 31 (2009) 213–222

Contents lists available at ScienceDirect

International Journal of Fatigue

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

The meaning of threshold fatigue in fibre metal laminates

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ARTICLE INFO

Article history:
Received 29 April 2008
Received in revised form 16 September 2008
Accepted 22 September 2008
Available online 1 October 2008

Keywords:
Fatigue crack growth
Fatigue threshold
Fibre metal laminates
Delamination
Glare

ABSTRACT

This paper discusses the meaning of threshold fatigue for fibre metal laminates under constant amplitude loading. A few experiments have been performed and the results are discussed in this paper.

1. Introduction

From the 1960s onward, fatigue crack growth phenomena have been analysed by many researchers to develop methods for fatigue and damage tolerance justification in metallic aircraft structures [1,2]. The crack stress method of Irwin [3] together with the correlation between stress intensity factor and crack growth rate presented by Paris et al. [4], has formed an excellent basis on which further research has been performed. However, the effect of crack closure discovered by Elber [5,6] and the ongoing research on the fatigue threshold behaviour has lead to different views on how to understand and to describe the observed crack growth behaviour in the different regimes.

The approach to correct stress intensity factors for effective crack opening induced by plasticity induced crack closure, has become a matter of dispute. Some authors claim that the crack growth behaviour should be described by a two-parameter stress intensity method instead of the stress intensity range only [7–13]. The effect of both K_{max} and ΔK should explain the observed behaviour. On the other hand, it can not be denied that some observed phenomena, such as delayed crack retardation, indicate the effect of crack closure in the wake of the crack tip [14]. Recent studies propose to quantify the effect of crack closure in a slightly different way, because the crack is believed to close further away from the crack tip, instead of at the crack tip [2,15].

Between all the scientific research performed on these topics, aircraft manufacturers attempt to justify their structural designs with respect to fatigue and damage tolerance with engineering methods. For instance, one reason to determine the values for the threshold fatigue stress intensity factor for materials is related to the practical world: the fatigue and damage tolerance justification of aircraft structures. To reduce the number of expensive and time-consuming flight spectra tests, accurate and reliable analysis methods are needed to perform the necessary strength justification. Fatigue simulation by means of calculations also requires time reduction for costs reasons. Assuming that below the threshold stress intensity factor no macro crack growth will take place enables defining omission levels, below which the loads are not taken into consideration [16]. This reduces the number of flight cycles in the simulation. A higher omission level means that more load cycles can be omitted and a further reduction of the load spectrum achieved.

However, application of these omission levels is only justified if it can be proven that the stress levels below this cut-off value do not add to the damage growth [16]. This requires clear definition of what the fatigue threshold means, but it needs also accurate determination of the threshold values. The motivation for defining a threshold value is not the same for engineering and scientific purposes. For engineering purposes, a safe cut-off value for loading which can reduce testing and analysis time is desired. Conversely, scientific research attempts to identify the true meaning of the fatigue threshold and relate it to identifiable mechanisms.

Considering the above-described aspects for monolithic aluminium alloy, the meaning of threshold fatigue in fibre metal laminates (FMLs) comes into question. The concept of FMLs has been developed at Delft University of Technology, initially with the objective to enhance the fatigue performance of laminated aluminium sheets [16,17]. This concept has been very successful in terms of increasing the fatigue life (compared to aluminium often by at

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doi:10.1016/j.ijfatigue.2008.09.008

Nomenclature

a	half crack length (mm)	N	number of cycles (–)
a_0	initial half crack length (mm)	N_{tot}	total number of cycles (–)
b_0	half delamination length at started notch tip (mm)	n	constant in Paris crack growth relation (–)
C	constant in Paris crack growth relation (–)	R	stress ratio (–)
E	Young's modulus (MPa)	R_{al}	stress ratio in aluminium layers (–)
E^*	dimensionless stiffness parameter (–)	S	stress (MPa)
f	frequency (Hz)	t_{al}	aluminium layer thickness (mm)
G	shear modulus (MPa)	t_f	fibre layer thickness (mm)
G	strain energy release rate (MPa mm)	W	specimen width (mm)
K	stress intensity factor (MPa $\sqrt{\text{mm}}$)	w	bar element width (mm)
$K_{bridging}$	stress intensity factor as result of bridging (MPa $\sqrt{\text{mm}}$)	x	coordinate parameter (mm)
$K_{farfield}$	stress intensity factor due to far field stresses (MPa $\sqrt{\text{mm}}$)	α	scale factor (–)
K_{th}	threshold stress intensity factor (MPa $\sqrt{\text{mm}}$)	β	geometry correction factor (–)
K_{tip}	stress intensity factor at the tip (MPa $\sqrt{\text{mm}}$)	β_d	factor characterizing effect of delamination shape (–)
L	specimen length (mm)		

least a factor of 10!). For a long time researchers have investigated the fatigue behaviour of various FMLs, and have attempted to describe the fatigue crack propagation behaviour using linear elastic fracture mechanics. Reviewing the literature on this topic [18] makes clear that the maximum stress intensity factor in a FML cannot simply be described by

$$K_{max} = \beta S_{max}\sqrt{\pi a} \quad (1)$$

where β is the factor correcting for geometry effects [3]. Despite the evident influence of the applied laminate stress in the crack growth behaviour, no clear relation can be derived between the stress intensity factor at the crack tip and the applied laminate stress. The load transfer over the crack via the intact fibre layers, often denoted as 'fibre bridging', induces a different stress field near the crack tip in the metal layers. In addition, this fibre bridging induces and is affected by delamination at the interfaces, which adds to the complexity of the fatigue crack growth mechanism. Besides making the description of the fatigue behaviour with Eq. (1) nearly impractical, such a description would also be physically meaningless.

While investigating the fatigue crack growth behaviour of the FML Arall, Marissen [19] and later on Guo and Wu [20,21] concluded that the stress intensity factor should be described using the superposition principle

$$K_{tip} = K_{farfield} - K_{bridging} \quad (2)$$

Although this conclusion physically made sense, the proper description of $K_{bridging}$ has been a problem for a long time, leading to empirical correction factors in several relations to describe the overall crack growth behaviour accurately. Recently, a model has been derived based on Eq. (2) and a similar expression for the crack opening contour [23,24], providing a physically sound model without the need for additional fitting parameters applied in previous models.

In general, it was concluded that in addition to the material properties of the laminate constituents, the crack growth behaviour of the metal constituent, described by a Paris relation, and the delamination behaviour at the interface are needed as input for the calculation. This conclusion was further supported by the research of Plokker et al. [25], who showed that the crack closure relation derived by Schijve for monolithic aluminium alloy 2024-T3 [26] is also valid for the aluminium layers in Glare. Furthermore, the delamination behaviour can easily be determined with experiments and related to the energy release rate [27,28].

Now that it is understood that the fatigue crack growth mechanism in FMLs can be described using a superposition principle, separating the metal and fibre contribution, the question arises whether this also holds for threshold fatigue aspects. For that purpose, experiments performed at Delft University of Technology that have not been reported before in the open literature [30] have been analysed again. Based on the analysis of these crack growth tests and on previously reported knowledge on fatigue crack propagation in FMLs, this paper discusses the meaning of fatigue threshold as it applies to FMLs.

2. Experimental fatigue threshold procedure

2.1. Fatigue threshold in aluminium

In general, for monolithic metals, there are various experimental approaches to determine the fatigue threshold. Some of these approaches are described in testing standards [31], while other approaches have been proposed and published in the literature [32,33–36]. The three most common approaches to decrease ΔS to determine ΔK_{th} are illustrated in Fig. 1.

The variety of procedures proposed is a result of the discussion about how to properly determine the threshold value and whether or not it is a material parameter. For example, the stress reduction approaches (a) and (c) in Fig. 1 have to be applied carefully to avoid any retardation effect on the observed crack growth data [16]. In addition, the fatigue threshold seems not to be a material parameter as a dependency of stress ratio has been observed [37]. This implies that approach (c) in Fig. 1 should be applied rather than the other two, in order to obtain results at the same stress ratio level.

The difference in threshold behaviour for short cracks and long cracks is also mentioned to discussions on the nature of this value [16,38–40]. Some authors acknowledge these effects and attribute these dependencies to the presence of residual stresses. As a result, they propose that fatigue tests with additional compliance corrections can be completed to arrive at a threshold value that can be considered a material property [34–36]. Their research is based on the extensive experience of fatigue testing of forged components, where the residual stresses depend on the way the specimens are being cut from the base material. Excluding the effect of residual stresses and clamping effects reduces the scatter in the near threshold region of the $da/dN{-}\Delta K$ curve significantly.

2.2. Fatigue threshold experiment on FML coupons

Aside from all the research and discussions on the best approach towards determining threshold values, research has been performed on fatigue crack growth in FMLs [19–21]. Since fatigue