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Delamination fatigue growth in polymer-matrix fibre composites: A methodology for determining the design and lifing allowables

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ABSTRACT

The introduction, originally in 2009, by the FAA of a 'slow growth' approach to the certification of polymer-matrix fibre composites has focused attention on the experimental data and the analytical tools needed to assess the growth of delaminations under cyclic-fatigue loads. Of direct relevance is the fact that fatigue tests on aircraft composite components and structures reveal that no, or only little, retardation of the fatigue crack growth (FCG) rate occurs as delamination/impact damage grows. Therefore, of course, the FCG data that are ascertained in laboratory tests, and then employed as a material-allowable property to design and life the structure, as well as for the development, characterisation and comparison of composite materials, must also exhibit no, or only minimal, retardation. Now, in laboratory tests the double-cantilever beam (DCB) test, using a typical carbon-fibre reinforced-plastic (CFRP) aerospace composite, is usually employed to obtain fracture-mechanics data under cyclic-fatigue Mode I loading. However, it is extremely difficult to perform such DCB fatigue tests without extensive fibre-bridging developing across the crack faces. This fibre-bridging leads to significant retardation of the FCG rate. Such fibre-bridging, and hence retardation of the FCG, is seen to arise even for the smallest values of the pre-crack extension length, $a_p - a_0$, that are typically employed. The results from the DCB tests also invariably exhibit a relatively large degree of inherent scatter. Thus, a methodology is proposed for predicting an 'upper-bound' FCG curve from the laboratory test data which is representative of a composite laminate exhibiting no, or only very little, retardation of the FCG rate under fatigue loading and which takes into account the inherent scatter. To achieve this we have employed a novel methodology, based on using a variant of the Hartman-Schijve equation, to access this 'upper-bound' FCG rate curve, which may be thought of as a material-allowable property and which is obtained using an 'A basis' statistical approach. Therefore, a conservative 'upper-bound' FCG curve may now be calculated from the DCB laboratory test data for material development, characterisation and comparative studies, and for design and lifing studies.

1. Introduction

The growth of delaminations in polymer-matrix fibre composites under cyclic-fatigue loading in operational aircraft structures is an important factor which has the potential to significantly affect the service-life of the airframe. In this context it is important to note the introduction [1], originally in 2009, by the Federal Aviation Administration (FAA) of a 'slow growth' approach to the certification of such composites and the examples of delamination growth in aircraft components and structures which have been reported in the open literature, see [2,3] for more details. These aspects have focused attention on the experimental data, and the analytical tools, needed to assess the growth of such delaminations under fatigue loads. One of the most common methods employed to assess the fatigue delamination resistance of fibre-reinforced plastics (FRPs) is to use a fracture-mechanics approach [2,4–39] to determine experimentally the dependence of the fatigue crack growth (FCG) rate upon some function related to the applied energy release-rate, G, in the fatigue cycle. Therefore, the present paper addresses the growth of delaminations in FRPs under cyclic-fatigue loading using such an approach.

Now, of direct relevance is the fact that previous studies on actual aircraft components and structures have revealed no, or only little, retardation in the (delamination) FCG rate. For example, in [2,40–44] it has been shown that the fastest growing, i.e. lead, delaminations that arise under the cyclic-fatigue loading of aircraft components with mis-drilled holes, ply drop-offs, impact damage, manufacturing defects, etc.

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Nomenclature

a	total crack (delamination) length, measured from the loading line
a_0	length of the initial delamination in the test specimen, i.e. the length of the (thin) film used as a starter crack, measured from the loading line
a_p	length of the pre-crack (pre-delamination), measured from the loading line, in the test specimen prior to any cyclic-fatigue fracture measurements being taken
$a_p - a_0$	pre-crack (pre-delamination) extension length in the test specimen prior to any cyclic-fatigue fracture measurements being taken
A	a constant in the Hartman-Schijve equation
A_0	value of A when the value of $(a_p - a_0)$ tends to zero
CDF	crack driving force
CFRP	carbon-fibre reinforced-plastic
da/dN	rate of fatigue crack growth per cycle
D	intercept in the Hartman-Schijve crack-growth equation
DCB	double-cantilever beam
F_{max}	maximum load applied during the fatigue test
F_{min}	minimum load applied during the fatigue test
FAA	Federal Aviation Administration
FCG	fatigue crack growth
FRP	fibre-reinforced plastic
G	energy release-rate
G_c	quasi-static value of the fracture energy
G_{c0}	quasi-static value of the initiation fracture energy for the onset of crack growth
G_{max}	maximum value of the applied energy release-rate in the fatigue cycle
G_{min}	minimum value of the applied energy release-rate in the fatigue cycle
G_{tip}	value of G at the tip of the delamination in the absence of fibre bridging
ΔG	range of the applied energy release-rate in the fatigue cycle, as defined below
ΔG	$= G_{max} - G_{min}$
$\Delta\sqrt{G}$	range of the applied energy release-rate in the fatigue cycle, as defined below
$\Delta\sqrt{G}$	$= \sqrt{G_{max}} - \sqrt{G_{min}}$
$\Delta\sqrt{G_{th}}$	the value of $\Delta\sqrt{G}$ corresponding to a FCG rate, $da/dN = 10^{-10}$ m/cycle
$\Delta\sqrt{G_{thr}}$	range of the fatigue threshold value of $\Delta\sqrt{G}$, as defined below
$\Delta\sqrt{G_{thr}}$	$= \sqrt{G_{thr.max}} - \sqrt{G_{thr.min}}$
$\sqrt{G_{thr.max}}$	threshold value of $\sqrt{G_{max}}$
$\sqrt{G_{thr.min}}$	threshold value of $\sqrt{G_{min}}$
$\Delta\sqrt{G_{thr0}}$	value of $\Delta\sqrt{G_{thr}}$ when the value of $(a_p - a_0)$ tends to zero
K	stress-intensity factor
K_{max}	maximum value of the applied stress-intensity factor in the fatigue cycle
K_{min}	minimum value of the applied stress-intensity factor in the fatigue cycle
ΔK	range of the applied stress-intensity factor in the fatigue cycle, as defined below
ΔK	$= K_{max} - K_{min}$
n	exponent in the Hartman-Schijve crack-growth equation
N	number of fatigue cycles
R	stress ratio $(= F_{min}/F_{max})$
R^2	the linear correlation coefficient
W	strain-energy density
I, II	subscripts indicating Mode I (opening tensile) and Mode II (in-plane shear) loads

show no, or only very little, retardation.

Therefore, a first main requirement is that the FCG rate results that are ascertained from fracture-mechanics tests undertaken in the laboratory, and subsequently employed for certification or aircraft sustainment analyses, must also exhibit no, or only minimal, retardation. Only if this is the case may the FCG rate data obtained from such laboratory tests be reliably employed as material-allowable properties to design and life composite components and structures, as well as for the development, characterisation and comparison of composite materials. However, in fracture-mechanics tests, such as when the very commonly-used Mode I double-cantilever beam (DCB) specimen is employed, retardation of the FCG arising from fibre-bridging developing across the faces of the delamination as the fatigue crack advances is invariably observed and, as discussed in detail below, the development of such fibre-bridging cannot readily be prevented. Indeed, even if multidirectional or quasi-isotropic lay-ups, as opposed to unidirectional laminates, are employed for the DCB tests, then fibre-bridging, or even multiple-ply cracks leading to ply-bridging, generally still develop, as discussed later in the present paper.

A second main requirement for any methodology used to determine FCG rate data as a function of *G*, where this relationship could be considered as an accurate and valid material-allowable property, is to take into account the relatively large inherent scatter that is observed in the laboratory tests, whatever its source. It is now appreciated [2,16,19,21,24,28,32–37,39] that fibre-bridging effects may give rise, at least in part, to the relatively large scatter that is typically seen in fatigue tests on FRPs. However, there are other likely sources of such scatter [2,16,19,25,33]. These include, for example, (a) any variability in the manufacturing procedures, which can lead to variability in the composite laminate test specimens, and (b) experimental difficulties associated with accurately measuring the crack length and the relatively very low loads and displacements associated with such tests, especially as the test approaches the threshold region below which no significant FCG occurs.

From the above comments, it is therefore obviously of little use to determine an ‘average’ delamination growth curve from the fracture-mechanics tests undertaken in the laboratory. The same comments hold with respect to determining an accurate and valid value of the fatigue threshold, below which no significant FCG occurs. Clearly, the fracture-mechanics fatigue tests should be performed in order (a) to determine a delamination FCG curve that focuses on ensuring that the fastest possible growth curve is measured, i.e. one which is free of retardation effects, and (b) to assess quantitatively the typical scatter that is always observed with such measurements. However, the experimental data reveal that retardation effects, e.g. from fibre-bridging, and a relatively high degree of inherent scatter cannot usually be avoided. Thus, a methodology is needed for estimating an ‘upper-bound curve’ from the laboratory test results that (a) that encompasses all the experimental data considered by the present authors, (b) provides a conservative FCG curve which accounts for any retardation effects, and (c) accounts for the experimental scatter that is frequently seen under fatigue loading. Such an ‘upper-bound’ FCG curve can then employed for developing, characterising and comparing different composite materials, and for designing and lifing in-service aircraft components and structures, using a ‘slow growth’ approach.

The recent paper [2] proposed a novel methodology, based on using a variant of the Hartman-Schijve equation [45], to determine a valid ‘upper-bound’ FCG curve, which may be thought of as a material-allowable property and accounts for both fibre-bridging effects and experimental scatter. The aim of the present paper is, therefore, to investigate whether this methodology can be extended to a carbon-fibre reinforced-plastic (CFRP) composite for which a very extensive testing