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Characterisation of fatigue crack growth and related damage mechanisms in FRP–metal hybrid laminates

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Abstract

Fatigue crack growth and related damage mechanisms were investigated experimentally in a hybrid laminate consisting of carbon fibre-reinforced epoxy and an aluminium alloy. During the fatigue cycling, the strain within a defined area in the vicinity of the crack was measured directly using embedded fibre-optic Bragg grating sensors. The progress of delamination damage was monitored by means of an in situ ultrasonic C-scanning technique. A simplified empirical model has been applied to determine an effective stress intensity factor applied to the crack tip in the alloy material. Fatigue crack growth rate in the hybrid laminate, characterised using the effective stress intensity factor, was demonstrated to be in reasonable agreement with the data for the monolithic aluminium alloy, showing that the methods used to partition the load were reliable. The paper thus demonstrates a viable technology for in situ strain measurements, offers a new insight into the damage mechanisms that prevail in hybrid laminates, and validates simplified procedures for estimating crack growth.

Keywords: A. Fibre-reinforced metal laminates; B. Fatigue; C. Delamination; D. Ultrasonics; D. Fibre-optic strain sensors

1. Introduction

Developed primarily for improved fatigue crack growth (FCG) resistance, hybrid laminates are advanced aerospace materials consisting of alternately bonded fibre-reinforced polymer (FRP) and aluminium alloy laminae. The laminates are of lower density and higher strength than the simple aluminium alloy monolith, and are suitable for lower wing skin or fuselage components. Development of these materials has progressed steadily since ARALL (aramid fibre-reinforced aluminium laminate) was first reported [1]. In addition to improved fatigue performance, both carbon fibre-reinforced (CARALL) and glass fibre-reinforced (GLARE) aluminium laminates offer higher stiffness [2,3]. GLARE is one of the novel materials to be employed on the Airbus A380 aircraft, offering improved fatigue, corrosion and impact resistance, as well as significant weight saving [4,5].

The response of hybrid laminates to fatigue cracking at fastener holes is of particular interest in structural design. The behaviour is typically one of fatigue cracking confined to the alloy laminae, and delamination between the composite and alloy layers [6–12]. Although there is sometimes a deterioration in the integrity of the FRP laminae in the vicinity of the fatigue crack, there is a tendency for the reinforcing fibres to 'bridge' the flanks of the crack. This improves FCG resistance by restraining the opening of the crack in the aluminium alloy layers. In order to model

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FCG in these materials it is necessary to understand the damage propagation mechanisms and to characterise them parametrically.

The advent of fibre-optic sensor technology has made it possible to obtain a quantitative description of the strain field within the FRP layers. The principles upon which fibre-optic sensors operate are well established. In-fibre Bragg gratings written into the waveguide reflect light of a characteristic peak reflective wavelength, and can be used to sense either strain or temperature since these parameters change the peak reflective wavelength of the grating by altering the Bragg spacing [13]. The application of such sensors is particularly well suited to fibre-reinforced plastics because of the small size and unobtrusive nature of the optical fibre, but could equally find application in any structure or component utilising a low temperature setting matrix. At higher temperatures the grating will be annealed and its reflectivity deteriorates [14] so that Bragg grating sensors are not normally used at temperatures above 200 °C [15]. The advantages of in-fibre sensors have been exploited to monitor the structural health of working structures, such as marine vessels [16–19] and bridges [20], and Fabry–Perot sensors have been used to monitor the cure process and detect vibration in polymer composites [21]. The uniform cylindrical nature of the fibre reduces the problem of stress concentration that would occur if conventional electrical (i.e. resistive) strain gauges were embedded. When embedded parallel to both the reinforcing fibres and the loading direction, the sensors have little effect on the mechanical behaviour of unidirectional laminates [22,23].

At the University of Southampton, a multiplexed grating interrogation system for addressing serial arrays of in-fibre gratings was successfully constructed. It was based on the use of a broadband source and an acousto-optic tuneable filter (AOTF) to determine the peak grating wavelength [24–29]. By embedding a two-dimensional array of sensors within the composite, a method was developed to map the strain field within the FRP layer of a CARALL panel subjected to fatigue damage [30,31]. The purpose of this paper is to illustrate how such strain mapping may quantify the redistribution of stress within the laminate as crack growth proceeds. Furthermore, we seek to demonstrate that a simplified analytical approach gives an adequate estimate for the effective stress intensity factor range, ΔK_{eff}, in the metal at the crack tip. The limitations of the simplified model are recognised and are discussed in this paper. However, its application requires limited materials property data and it has provided a vehicle for comparing results obtained from three different experimental techniques.

Although CARALL is not normally used as a structural material because of its known tendency to corrode, the aim of this work was to investigate the use of the fibre-optic system to monitor damage evolution. Carbon fibre-reinforced plastic (CFRP) was chosen because it is common in many aerospace applications, and there is still scope for development of embedded fibre-optic sensors to monitor their performance. Any model that characterises the mechanical behaviour of CARALL should apply equally well to other hybrid laminates.

2. The effective stress intensity factor, K_{eff}

As fatigue cracks grow in the aluminium alloy, and the alloy skins debond from the fibre-reinforced core in the wake of the crack, the FRP in the crack wake continues to bear a proportion of the load, so that the stress intensity factor, K, at the crack tip is effectively reduced. This phenomenon is commonly termed crack tip shielding.

The nominal stress intensity factor range applied to the whole laminate, ΔK_{lam}, is given by:

$$\Delta K_{\mathrm{lam}} = \frac{\Delta P}{Wt}\sqrt{\pi a \sec\left(\frac{\pi a}{W}\right)} \tag{1}$$

where ΔP is the applied load range, W and t are the width and thickness of the test panel, respectively, and $2a$ is the total crack length for a centre cracked panel in accordance with the test standard [32].

The stress intensity factor range applied to the metal skins, ΔK_{a}, is:

$$\Delta K_{\mathrm{a}} = \Delta S_{\mathrm{a}}\sqrt{\pi a \sec\left(\frac{\pi a}{W}\right)} \tag{2}$$

where ΔS_{a} is the stress range applied to the metal. In the simple case of a laminate comprising of a single unidirectional composite lamina sandwiched between two metal skins, ΔS_{a} can be expressed by:

$$\Delta S_{\mathrm{a}} = \frac{E_{\mathrm{a}}t_{\mathrm{a}}}{E_{\mathrm{a}}t_{\mathrm{a}} + E_{\mathrm{c}}t_{\mathrm{c}}}\left(\frac{t}{t_{\mathrm{a}}}\right)\frac{\Delta P}{Wt} \tag{3}$$

where E is Young's modulus and t is the thickness, and the subscripts a and c refer to the alloy skins and FRP core, respectively.

To account for the crack shielding provided by the bridging fibres of the FRP and to estimate ΔK_{eff} at the crack tip in the alloy, two techniques have been investigated, based on the compliance of the test-piece [8] and the closure stress in the aluminium alloy [9], respectively.

2.1. Compliance method

The compliance, C, is defined as:

$$C = \frac{Etv}{P} \tag{4}$$

where v is the centre line displacement at a load P, and E is Young's modulus of the laminate. The bridging by the FRP constrains the crack opening displacement so that at a given crack length the measured compliance is lower than that of the unreinforced alloy. By taking into account the load-partitioning between the constituents of the laminate, and by comparing the measured compliance, C_{m}, with the