



Evolution of residual stress during fatigue crack growth in an aluminium specimen with a bonded crack retarder



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ARTICLE INFO

Article history:
Available online 4 June 2014

Keywords:

Bonded crack retarders
Fatigue
GLARE
Residual stress
Structural composites

ABSTRACT

The application of bonded crack retarders in critical aircraft integral structures has been of great interest recently for the improvement of damage tolerance. One potential disadvantage of bonded crack retarders is that the thermal residual stresses which are developed during the strap bonding process are detrimental to the performance of the structure. This investigation explores the distribution of thermal residual stresses developed in an aluminium substrate reinforced with GLARE (glass-fibre-reinforced epoxy) straps and the evolution of stresses during fatigue crack growth. Residual stress measurements were performed using neutron diffraction. The results show that tensile residual stresses are developed in the aluminium substrate as a consequence of the strap bonding process. *In situ* residual stress measurements during constant amplitude fatigue crack growth were performed and it was observed that the growth of the fatigue crack altered the initial residual stress.

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1. Introduction

The demand for commercial air travel has significantly increased in recent decades. There has been a strong drive for increased design life and reduced operating costs for aircraft, and various technologies have been developed and deployed to this end. Major aspects in cost reduction include increasing fuel efficiency, reducing weight, and by reducing the operating or maintenance costs of the aircraft. Of these, weight reduction and maintenance cost are the priority factors. Aircraft are made of assemblies of various parts with numerous structural joints. The joints are typically riveted and bolted, and they require regular inspection and maintenance. Joints are fatigue critical locations during service, and add weight to the structure. One promising solution is to replace them by so-called “integral” structures based on machining (and possibly welding), which substantially reduce the weight, production cost and maintenance cost of the aircraft by reducing the number of joints.

The major problem associated with integral structures is that they lack the natural crack stopping features that are present in riveted and bolted joint structures. One solution is to incorporate

specialty-designed crack retarding features. Such features require low weight so as not to remove the weight savings associated with the integral structure, as well as fatigue resistance, damage tolerance and low maintenance requirements. Candidate materials need extensive research to ensure safety, structural integrity and damage tolerance of the aircraft [1,2].

Glass Laminated Aluminium Reinforced Epoxy (GLARE) fibre metal laminates have been developed in recent years, combining the superior properties of both metallic and fibre structures and offering lower density, higher strength and damage tolerance with much greater fatigue crack resistance than conventional aluminium alloys [3]. GLARE consists of alternate layers of aluminium sheet and glass reinforced epoxy. The orientation of the glass fibres in the adhesive can be varied according to the desired application. The high damage tolerance of GLARE is attributed to the aluminium whereas the high strength of GLARE laminates is derived from the strength of the glass fibres. The resistance to the initiation of fatigue cracks is controlled by the resistance of the aluminium sheet, while the resistance to the growth of the fatigue cracks is attributed to the bridging effect of the fibres and to some extent the controlled debonding at the epoxy–aluminium sheet interface. Furthermore, blunt notch strength, impact, corrosion and flame resistance of GLARE are superior to conventional aluminium alloys [4–10].

Aircraft must be designed to continue in service even after the accumulation of damage within the structure by fatigue or other failure mechanisms. Design features such as multiple load paths

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and bonded crack retarders are an integral part of safe, damage-tolerant design [2,11,12]. There has been considerable research on the usage of composite patches as bonded crack retarders in aircraft structural repairs and these have proven effective in increasing the service life of the structure [13–17].

The principle of a bonded crack retarder is to adhesively fix a stiffening strap to critical structural locations. The local increase in stiffness reduces the local driving force for crack growth by reducing the stress in the substrate. Extensive research performed on different strap materials shows GLARE as the most promising material to improve the fatigue life. The major disadvantage of bonded crack retarders is the generation of thermal residual stresses during the high-temperature adhesive curing in the strap bonding process, owing to coefficient of thermal expansion mismatch between the strap and substrate [18–23]. Induced thermal residual stresses may cause an adverse effect on the mechanical performance of the reinforced structure. Furthermore, single sided reinforcing can also result in out-of-plane distortion of the structure which may have significant effect on the mechanical performance [20,23]. Hence the primary objective of this investigation is to study the out-of-plane distortion and residual stresses developed in a single-sided reinforced specimen, and the evolution of the residual stress during subsequent fatigue crack growth.

2. Experimental materials and methods

2.1. Materials

Table 1 shows the mechanical properties of materials used in this investigation. The test geometry was a middle-crack tension (M(T)) specimen made from aluminium alloy 2624-T351, 400 mm long, 140 mm wide and 5 mm thick. Before bonding the straps, a crack-starter notch of 20 mm was made using electro-discharge machining (EDM). GLARE 2–6/5 (0.4) was chosen for the reinforcing straps, which consists of six layers of aluminium alloy sheets and five double layers of unidirectional glass fibres reinforced in epoxy. The specimen was prepared at Cranfield University. The assembly was bonded using FM94[®] adhesive supplied by Cytec Ltd. The curing temperature of FM94 was 120 °C. After cure the specimens were inspected using an ultrasonic phased array C-scan to confirm the bond quality.

The specimen was prepared with a global stiffness ratio (μ) of 0.2 defined as

$$\mu = \frac{\sum (E_{\text{strap}} \cdot A_{\text{strap}})}{(E_{\text{Al}} \cdot A_{\text{Al}}) + \sum (E_{\text{strap}} \cdot A_{\text{strap}})} \quad (1)$$

where E_{strap} , E_{Al} and A_{strap} , A_{Al} correspond to the elastic modulus and total cross-sectional areas of the straps and the aluminium substrate respectively. The dimensions of the straps were 180 mm long, 25.83 mm wide and 3.7 mm thick. The front edge of each strap was placed at 3.5 mm from the edge of the EDM notch: thus the distance between the front edge of the strap and the centre of the substrate

was 13.5 mm. Fig. 1 shows the geometrical details of the specimen used in this investigation. The direction along the longest dimension is hereafter referred to as the longitudinal direction (X), the direction across the width dimension is referred to as the transverse direction (Y), and the distance through the thickness is referred to as the normal direction (Z), as shown in Fig. 1.

3. Experimental methods

Prior to residual stress measurements and after specimen preparation an out-of-plane deflection was observed in the specimen. This is a consequence of the single-sided strap bonding, and it occurs because of the difference in coefficient of thermal expansion between the substrate and the strap. This deflection may have a detrimental effect on the fatigue and delamination behaviour of the specimen, and therefore it was important to quantify it. Deflection measurements were performed using a laser co-ordinate measurement machine on the un-reinforced side along the longitudinal direction, with a measurement pitch of 1 mm.

Residual stress measurements were performed using neutron diffraction. Neutron diffraction is a well-established non-destructive technique to determine lattice strain in a crystalline material. Neutron diffraction works on the principle of Bragg's law (Eq. (2)) which explains the relationship between the wavelength of the scattering neutrons λ and lattice spacing d_{hkl} of atomic planes described by Miller indices (hkl), and the corresponding diffraction angle $2\theta_{\text{hkl}}$ [24]. If both inter-planar distances of stressed (d_{hkl}) and unstressed or stress-free (d_0) material are known, strain in a particular direction can be computed by using Eq. (3) and thereby the stress in particular direction using Hooke's law.

$$n\lambda = 2d_{\text{hkl}} \sin \theta_{\text{hkl}} \quad (2)$$

$$\varepsilon(x, y, z) = \frac{d(x, y, z) - d_0}{d_0} \quad (3)$$

where ε represents strain, and $d(x, y, z)$ represents the inter-planar distance in the bonded sample.

Residual stress measurements were performed at ENGIN-X at the UK's ISIS neutron source, which is a time of flight (TOF) diffractometer where multiple reflections can be measured. Fig. 2 shows the experimental setup for residual stress measurements at ENGIN-X. ENGIN-X Script Based Analysis (EX-SBA) was used for the data analysis where Pawley refinement was used to determine the lattice parameters: this has been shown to yield a good approximation of the engineering strain in a material [25,26]. A gauge volume, defined by the intersection of the incident and scattered beams of the neutrons, of $2 \times 2 \times 2 \text{ mm}^3$ was used for all the measurements. As the substrate is rolled in the longitudinal direction, texture and plastic anisotropy will be present which results in significant variation in the lattice parameters in all three directions (longitudinal, transverse and normal). Therefore the inter-planar distance in the stress-free sample had to be measured in all three directions. Stress-free reference measurements were performed at a point well outside of the bonded area close to an edge; these were used to provide the stress-free values in the computation of residual stresses.

All the residual stress measurements were performed in the substrate along the crack growth direction (y -direction) in two different thickness locations, $z = 1.5$ and 3.5 mm from the reinforced side as shown in Fig. 1. Measurements were performed at four crack lengths: 10, 17, 26.5 and 48 mm from the centre of the specimen (10 mm corresponds to the initial condition with a starter notch before a fatigue crack is grown. Owing to time constraints, measurements at the 48 mm crack length were made only at $z = 1.5$ mm.

Table 1

Mechanical properties of materials used in this investigation. E = elastic modulus; ν = Poisson's ratio; α = coefficient of thermal expansion; ρ = density.

	Al 2624-T351	GLARE constituents	
		Al 2024-T3	FM94/S2-prepreg
E_1/GPa	73	72	50.3
$E_2, E_3/\text{GPa}$	71	72	5.5
$\nu_{12} = \nu_{13}$	0.33	0.30	0.310
ν_{21}	0.33	0.30	0.034
$\alpha_1/^\circ\text{C}^{-1}$	2.32×10^{-5}	2.32×10^{-5}	2.88×10^{-6}
$\alpha_2/^\circ\text{C}^{-1}$	2.32×10^{-5}	2.32×10^{-5}	4.03×10^{-5}
$\rho/\text{kg m}^{-3}$	2770	2770	1972

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