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Fatigue performance of bonded crack retarders in the presence of cold worked holes and interference-fit fasteners

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ABSTRACT

Bonded crack retarders (BCR) are of particular interest in the aerospace applications for improving fatigue performance of airframe structural assemblies. In respect of structural integrity, a reinforcing strap will require additional fixing by means of riveting or bolting to ensure fail-safety. Cold expansion is currently the common practice of increasing the fatigue performance of fastener holes. Thermal residual stresses introduced during the adhesive curing process at 120 °C for strap bonding are of potential concern as they may affect the cold expansion stresses and thereby the fatigue crack growth performance of the fastener hole and reinforced structural assembly. In this paper, Single-Edge-Notched Tension (SENT) specimens are made of aluminium alloy 2624-T351. Fibre metal laminate GLARE is used as BCR strap. SENT specimens with BCR and with BCR plus an interference fit fastener are used to investigate the fatigue crack growth performance. Residual stress was measured by neutron diffraction method on specimens with BCR plus fastener. It is found that the GLARE strap provides a 2.3 × improvement in life comparing to a plain specimen, and a 1.75 × life improvement when a fastener is installed in a cold expanded hole.

1. Introduction

Aircraft structures experience considerable fatigue loading during their service life that imposes significant inspection and maintenance costs for aircraft operators. The primary source of fatigue-based problems is the stress concentrations associated with the numerous assemblies joined by rivets and fasteners. Therefore, the aircraft industry is working towards new design concepts for airframes, maintaining a high level of safety without any weight penalty and/or increase in manufacturing cost. One of the solutions is to use large one-piece integral structures to reduce the number of built-up assemblies. The major concern with integral structures is that they are prone to fatigue cracking owing to single load paths and fewer natural crack stoppers compared to conventional assemblies. As a result, the certification of integral metallic structures is often associated with further safety factor requirements, which leads to additional structural weight and negates the benefit of using integral structures.

To satisfy the damage-tolerance requirements of such structures, technologies have been developed such as selective reinforcement [1] also known as bonded crack retarders [2–4]. The application of bonded crack retarders has proven effective in increasing the fatigue performance of integral metallic structures. These are typically a combination of advanced alloy parts reinforced with highly damage-tolerant materials that are adhesively bonded together. Amongst various bonded crack retarder materials, GLARE fibre-metal laminate has been considered as the best candidate owing to low weight, low thermal residual stresses after bonding at elevated temperature, and excellent fatigue and impact performance [5–10]. Therefore, GLARE was chosen as the crack retarder material for this research.

Despite the benefits of bonded crack retarders, secondary bending and thermal residual stresses are two concerns. Secondary bending is a consequence of the single-sided strap bonding process and this can affect the fatigue performance of the reinforced structure. Whilst secondary bending can be reduced by double-sided strap bonding, this is unlikely to be deployed in aircraft

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manufacture owing to the aerodynamic requirements of the exterior surface of the reinforced structure.

The use of adhesive instead of rivets or bolts to join substrate and reinforcements allows full exploitation of the benefit of integral structures. However, adhesively bonded straps require an additional means of fixing, either by rivets or fasteners, to ensure structural fail-safety in the event of complete disbond. Such fixings require drilling holes that introduce stress concentration. The stress concentrations can be reduced and the fatigue performance of fastener holes can be enhanced by the cold expansion process [11]. Fatigue crack growth performance of a reinforced structure that contains cold expansion stresses and a fastener has not been investigated prior to this research.

In addition, drilling fastener holes through the reinforced structure can damage the GLARE and the adhesive bonding interface. Typical damage mechanisms that can occur are push-out or peel-up delamination, fibre-matrix debonding, and interlaminar cracking. Experimental tests and FE analyses performed in [12] revealed that drilling also leads to hole-edge quality issues, resulting in edge chipping and glass fibre damage. Such damage is highly undesirable, and can lead to delamination and the loss of mechanical strength and stiffness of the strap and reinforced structure.

To the authors' knowledge there is no previous work investigating the fatigue crack growth performance of aluminium 2624-T351 reinforced by bonded GLARE straps in the presence of a cold expanded hole with interference fit fastener. This study aims at investigating the potential of the bonded crack retarder concept in structural assemblies that have fasteners to ensure fail-safety with the intention of proving the technology for inclusion of integrally machined structures reinforced with bonded crack retarder in future aircraft designs. The focus is on the effect of the crack retarder in the presence of a fastener.

2. Materials and test specimen

Aluminium alloy 2624-T351 was used as the substrate material and fibre metal laminate GLARE 6/5 was chosen as the strap. The GLARE strap consists of six AA2024-T3 alloy sheets (0.4 mm thick) with five intermediate prepreg layers of unidirectional glass fibre-reinforced epoxy (0.26 mm thick) oriented along the longitudinal direction of the strap (X-axis, Fig. 1a). The geometry of the specimen with a strap is shown in Fig. 1a and the actual cross-section of the specimen is presented in Fig. 1b. Initial crack orientation is perpendicular to the rolling direction of the substrate. This orientation is determined by the application requirement. The thickness of the substrate and strap is 5.0 mm and 3.7 mm respectively. Mechanical properties of the substrate and strap are listed in Table 1. Before the strap bonding process, a 17 mm notch was machined in the substrate to act as a crack starter for the fatigue crack growth testing. The specimen configuration is shown in Fig. 1.

One important parameter that contributes to the performance of the BCR is the global stiffness ratio μ, which is defined as:

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

where E_{strap}, E_{Al} and A_{strap}, A_{Al} are the elastic modulus and cross-sectional area of the straps and the substrate material respectively. In this study a global stiffness ratio of 0.32 was chosen.

The surface of the substrate and the external aluminium sheets of the GLARE were etched with Phosphoric Acid Anodizing (PAA), which involves alkaline degreasing followed by PAA and priming with BR 127, a modified epoxy phenolic primer with corrosion inhibiting properties [14,15]. The substrate and strap assembly was bonded using FM 94 [16], a high-temperature (120 °C) curing adhesive. The curing process is described below.

- Apply vacuum at ambient temperature for a minimum of 15 min and increase the temperature at a rate of 3 °C/min from ambient to 125 ± 5 °C, and increase pressure in autoclave to 520 kPa.
- Vent vacuum when the pressure reached 415 kPa, or when the temperature reached 60 °C, then apply a pressure of 520 kPa at 125 °C for 90 min.
- After 90 min, turn off the heat and allow cooling to below 60 °C, whilst maintaining the pressure, prior to removing the samples from the autoclave.

To check the bond quality, specimens were inspected using an ultrasonic phased array device Olympus Omniscan Mx with a 5L64-I1 probe. A rolling wheel encoder was added to the probe in order to measure the scanning distance. The resolution of the encoder was 12 steps/mm.

After bonding, an interference fit fastener was installed through the thickness of the assembly. The interference fit fastener hole was 3% cold expanded using the FTI split-sleeve cold expansion and the final diameter of the fastener hole was 6.35 mm. During this procedure, the mandrel was pulled from the non-reinforced side (entry face) towards the reinforced side (exit face).

3. Experimental procedure

3.1. Grain size and texture measurements

The substrate material used in this investigation is formed by rolling; a strong preferred grain orientation will be developed in the specimen. When the material passes through the rollers, the interaction with the roll affects the homogeneity and grain size in three dimensions. Therefore, grain size measurements were performed in the rolling (X), transverse (Y) and normal (Z) directions. For this, three samples were extracted from the substrate, mounted, ground, polished, and etched with Keller's Reagent for 12 s.

3.2. Measurement of out-of-plane deformation

The specimens were subjected to in-plane loading in fatigue testing with loading along the material longitudinal direction (the X-direction, see Fig. 1). Owing to the asymmetric strap configuration (straps were bonded on one side of the plate only), out-of-plane deformation occurred after the curing of the straps, and additionally during the fatigue loading because of the secondary bending effect (see Fig. 3).

Following curing of the crack retarders at elevated temperature, residual stresses exist owing to the mismatch of the coefficient of thermal expansion between the aluminium substrate and the GLARE straps. Because of the asymmetric strap configuration, these residual stresses will cause out-of-plane deformation. This deflection was measured on the specimens after the strap bonding process using a coordinate measurement machine. The measurement was performed on the unreinforced (back) side along the specimen longitudinal direction (X) with a 1 mm measurement interval.

3.3. Residual stress measurements

Residual stress measurements were performed using neutron diffraction using the ENGIN-X instrument at the ISIS neutron source, UK; and the SALSA instrument at the ILL, France. Neutron