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On the static strength of aluminium and carbon fibre aircraft lap joint repairs

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ABSTRACT

The behaviour of various aircraft lap joint repair configurations is investigated experimentally and numerically under static loading. The lap joints consist of aluminium alloy (AA) 2024-T3 substrates repaired with twin single-sided AA 2024-T3 or Carbon Fibre Reinforced Epoxy (CFRE) doublers. Pure riveted, pure bonded and hybrid (riveted and bonded) joints of metal–metal and metal–composite configurations are investigated. From experimental results, joints with adhesive bond showed nearly 5 times higher average strength than pure riveted joints, while hybrid joints performed better than riveted and bonded joints because of higher stiffness. On the other hand, hybrid metal–metal joint has 70% higher average strength compared to hybrid metal–composite joint. Rivet-shear has caused failure of riveted joints, and adhesive failure is observed in pure bonded joints. Hybrid joints with metal doublers have failed initially due to adhesive failure and later rivet shear. Interestingly, net-section failure is observed in composite doublers with breakage of doublers due to the presence of holes in the doublers. Experimental results are complimented with numerical analysis using commercial finite element code ABAQUS. Load–displacement curves obtained from the numerical results are in good agreement with experiments with a marginal error of 2%. In addition to load–displacement curves, a detailed stress analysis is performed numerically on metal–metal and metal-composite joints under riveted, bonded and hybrid configurations to study stress distribution on substrate and doublers. Numerical analysis showed hybrid and bonded joints have lower stresses in substrate and doublers compared to the riveted joints. Bonded joints have smoother load transfer due to the adhesive spread over a larger area. And finally, Stress Intensity Factors (SIFs) are performed numerically for unreinforced and reinforced metal substrate with crack length of 1, 5 and 10 mm with metal and composite doublers under riveted and bonded configuration. For crack of 10 mm, 35% reduction in SIFs is observed for reinforced substrate with bonded metal or composite doublers compared to unreinforced cracked substrate.

1. Introduction

Airlines aim to operate at maximum efficiency by, for instance, reducing turn-around time between flights. During this time, aircraft are inspected for any structural damages. If any part of the aircraft is found to be damaged beyond the Federal Aviation Regulation (FAR) Part 25 standard by the Federal Aviation Administration, U.S. Department of Transportation, then it has to be repaired or replaced. Maintenance is part of operating costs which include repairs, overhauls and replacement of damaged parts. Hence, repair technologies play an important role in maintenance costs.

Aircraft structures are made from numerous small parts joined to form major assemblies, in which joining techniques play an important role. Most common methods of joining are by use of mechanical fasteners: rivets, bolts, nuts, etc. Other types of joints or repair techniques involve only adhesives or combination of fasteners and adhesives. Rivets are widely used in joining, for instance, the skin panels to stringers and spars to hold them in position. Rivets are easy to install with a short repair time, cost effective, and with high resilience and durability compared to adhesives [1]. The strength of solid rivets is better than blind rivets if both sides of the substrate are accessible, however, this is not possible in all cases. If only single-side access is possible, then blind rivets are used to repair cracked substrates with fastened doublers. In this study, joints are analysed with blind rivets to

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replicate single-side access. The strength of riveted joints depends on rivet hole diameter, material properties, squeezing force and fastening pattern [2–5]. Due to the riveting process, the holes made in the plate reduce the strength of the joint and cause high-stress concentrations [6,7]. Early failure of riveted joints in aircraft structures may be experienced due to the induced residual stresses during manufacturing [8,9]. Stress concentrations around the holes can be reduced by cold expansion [6,10], clamping force [16] and interference fit [11–13], increasing the static strength and fatigue resistance of the joints.

The fatigue behaviour of single- and double-rivet self-piercing riveted joints was investigated by Iyer et al. [14] by means of experiments and finite element analysis (FEA). These researchers used a 3D elastic finite element model and identified the gross section of crack initiation. Multiple crack propagation in aircraft skin-doubler riveted joints was investigated by Armentani et al. [15]. They compared the advantages and disadvantages of a dual boundary element method and a finite element model. A 3D finite element model was developed by Oskouei et al. [16] to simulate the clamping force and load transfer through the joint plates. This study showed that the stress concentrations can be reduced by increasing the clamping force under static tensile loads. Bolted joint structures were investigated by Kim et al. [17], who proposed four types of finite element models, developed with 3D solid elements and surface-to-surface contact elements between bolt head-flange interfaces, showing better agreement with experimental results among the other models.

Understanding failure modes have always been important in designing better structures. Sathiya et al. [18] studied the rivet load distribution in the failure and damage tolerant design of metal–metal and metal–composite civil aircraft lap joints. This study describes various methods of modelling rivet in FEA. Further experimental studies on riveted joints were conducted by Pavan et al. [19] and Chen et al. [20]. The latter researchers studied failure modes of riveted joints under tensile loading both experimentally and numerically, showing three possible failure modes for which the numerical results were in good agreement with the test results. The failure modes of fastened bolted joints can be classified into two types: basic failure and secondary failure [21,22]. The basic failure modes are further classified into three subtypes: net-tension, shear-out and bearing. The secondary failure modes are classified into cleavage and shear-out failure.

The role of geometric parameters in the design of fastened joints should also be considered. For instance, the further the holes from the edges, the higher the strength of the joint. Moreover, the length and width of the plates with respect to the dimensions of the fastener holes can effectively influence the failure mode of the joint [23,24]. The failure mode of metals and composites may depend also on loading conditions. Pisano et al. [25] investigated failure modes of multi-pin composite laminate joints due to fastening. For single-lap aluminium alloy (AA) 2024-T3 bolted joints, the effect of geometric variables on the stress–strain distributions and the nonlinear behaviour of the joint under tension was investigated by Keikhosravy et al. [26]. Nabil et al. [27] analysed the static and fatigue behaviour of thin riveted, bonded and hybrid composite lap joints.

Adhesive bonding of structures is also an effective way of joining aerospace and automotive parts. The strength of adhesive joints is higher than pure riveted joints; the stresses are evenly distributed along the bonded area and this makes the joint more stable with respect to stress intensity factors (SIF) and stress concentrations. Many studies have been conducted on adhesively bonded composite patches to repair cracked metallic plates [28–33]. Banea et al. [34] investigated the effects of surface preparation, joint configuration and adhesive properties on the response of adhesively bonded composite joints. Bending can be observed in adhesively bonded single-side composite patch repairs to metallic plates. Particularly, Clark et al. [35] investigated bending of bonded composite repairs on cracked AA 2024-T3 plates.

Hybrid joints (using both mechanical fasteners and adhesive) are another effective method of joining repair patches, achieving high durability [36–38]; if the adhesive fails due to the defective bond line or de-bonding, the mechanical fasteners can carry the load until the following inspection [39]. The high-stress concentrations around the fastener holes in pure riveted joints can be reduced by using an adhesive between the surfaces, which improves static strength and fatigue resistance. Hybrid joints are designed to carry shear loads since adhesive bonds are strong in shear and weak in peel [40]. Several investigations on hybrid joints have been reported in the literature [41–47]. It has been observed that debonding of the adhesive between the surfaces is the predominant cause of initial failure of hybrid joints.

In this research, static failure of riveted, bonded and hybrid aircraft lap joints was investigated through experiments and numerical analysis. The substrates were made from AA 2024-T3, and the behaviour of repairs made with AA 2024-T3 doublers was compared to that with carbon fibre reinforced epoxy (CFRE) doublers. In addition, a finite element model was developed in ABAQUS/explicit and was verified against the experimental results for the riveted, bonded and hybrid joints. Most of the research in the literature focuses on pure metallic riveted and bonded joints, but very few works can be found in the literature on metal–composite riveted, bonded and hybrid joints. Hence, this research will help improve the understanding of the advantages, behaviour and limitations of these joint configurations.

2. Materials and methods

2.1. Materials characterization

Metal substrates and doublers for experiments are prepared from a sheet of commercial AA 2024-T3. The T3 temper consists in solution heat-treatment at 480 °C for 1 h, followed by rapid water quenching to room temperature, cold-working and natural ageing. Tables 1 and 2 shows, respectively, the mechanical properties and composition (in wt.% and at.%) for AA 2024-T3, as provided by the supplier (Kaiser Aluminium fabricated products, Spokane, USA). Substrates are machine cut by Kaiser Aluminium into rectangular plates of dimensions 171.4 mm × 25.4 mm × 3.175 mm. Likewise, doubler 1 and doubler 2 are machine cut into plates of dimensions 215.9 mm × 25.4 mm × 1.5875 mm and 165.1 mm × 25.4 mm × 1.5875 mm (see Fig. 1).

A two-part thixotropic adhesive Araldite 2031, consists of resin and hardener, is used in preparation of bonded and hybrid joints. The term 'metal' corresponds to AA 2024-T3 and 'composite' corresponds to Carbon Fibre Reinforced Epoxy (CFRE). Because of bonding capability characteristic between metal–metal, metal-composite and composite-composite, Araldite 2031 is chosen for this investigation. Araldite 2031 is a toughened adhesive with high chemical resistance and has low shrinkage. The best performance can be achieved by curing the adhesive at 40 °C for 16 h. Table 3 shows the properties of Araldite 2031, as provided by the supplier (Huntsman Advanced Materials, Switzerland GmbH). Stress–strain curve for Araldite 2031 is shown in Fig. 2. Standard aluminium pop rivets (supplied by Rapid rivets, Hestra, Sweden) are used in preparation of riveted and hybrid joints.

Composite doublers are made of CFRE laminates with fibre in satin weave configuration of orientation 0^0 and 90^0 (manufactured and supplied by Composites Ate, S.L., Barcelona, Spain). Doublers are prepared by stacking six layers of plies, with ply thickness of 0.25 mm. Doublers stacking sequence is [(45/135)/(0/90)/(0/90)/(0/90)/(0/90)/(45/135)]. Stacking sequence satisfies eight golden rules used in the aerospace industry, to make sure the composite structure has

Table 1
Mechanical properties of aluminium alloy (AA) 2024-T3, as provided by the manufacturer (Kaiser Aluminium, USA).

Aluminium alloy	Yield stress	UTS	% Area Reduction	Brinell Hardness
AA 2024-T3	316 MPa	464 MPa	20.2%	HB 123