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Experimental and finite element studies of thin bonded and hybrid carbon fibre double lap joints used in aircraft structures

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ABSTRACT

Finite element analysis (FEA) is performed to verify the static and fatigue strength of mechanically fastened, bonded and hybrid double lap joints. These joints are made from thin carbon fibre/epoxy laminates applied in aircraft structures. Several configurations are considered, including variations in rivet array and the addition of bondline defects. Adhesive nonlinear material properties, rivet surface contacts and frictional forces were included in the three-dimensional (3D) Finite Element (FE) models. The Multicontinuum Theory (MCT) is used to simulate the progressive failure process and the stress state for all specimens, whilst the strain energy release rate (SERR) as a function of crack length for bonded and hybrid specimens are also compared. Results have shown the FE models are able to accurately predict the bonded, riveted and hybrid joint strengths. The position of the first row of fasteners is critical in determining the crack growth rate. As the crack enters the fasteners' clamping zone there is a significant drop in SERR resulting in a much slower crack growth rate, therefore increasing the fatigue resistance of the hybrid joint configuration.

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1. Introduction

Joints potentially act as weak links in structures, thus it is important to understand their strength and the mode in which they fail. The three common methods of joining composite laminates together is either through mechanical fastening, bonding or the combination of the two, called 'hybrid' joints. Mechanical fasteners such as pins, rivets and bolts have commonly been used in the aerospace industry for decades [1–4]. The key problem that arises through the use of mechanical fasteners is the high stress concentrations around the fastener holes which are more severe in composite laminates compared to metal plates [5].

Adhesively bonded joints are structurally more efficient than mechanically fastened joints as they perform better in distributing loads, eliminating a majority of the high stress concentration problems seen in bolted joints [6,7]. One underlying weakness associated with bonded joints is its process control during repair applications. Improper processes would result in a weak bond that is not generally possible to be detected by means of non-destructive inspection (NDI). The detrimental effect of some improper surface treatment may not even manifest in a significant reduction of the initial static strength of the bond but in an adverse impact on the durability of the adhesive bond at service temperature and moisture environment and/or under fatigue loading [8].

The combination of mechanical fastening and bonding has been employed to safeguard against defects within the adhesive layer which may cause premature or catastrophic failure [9]. It is only after the bond has failed where the fasteners begin to carry the remaining load in the joint. It is this safety factor that has allowed the certification of these joints in some aircraft structures.

A number of papers have investigated the use of hybrid lap joints. Hart-Smith [10] provided a non-linear analysis of bonded and bolted joints and concluded that hybrid joint configurations cannot achieve any significant advantage over adhesive bonding in well-designed intact structures, however it may prevent defect/damage propagation. Sun et al. [11] showed how the use of 'attachments' can allow fasteners to carry more load in a hybrid joint configuration; results were found experimentally and numerically using a two-dimensional model whereby the attachments increased joint strength by reducing peel stresses. Furthermore, Kelly [12] investigated the load distribution in hybrid joints with a single bolt using FEA.

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Hence in recent years the use of Finite Element (FE) methods to simulate the behaviour of composite joints has increased particularly due to the advancement of many FE packages. However, most composite hybrid joint models so far reported are restricted to 3D models with a single fastener or 2D models [9,13–17]. In order to be used as a versatile design tool, the analysis needs to be able to simulate multi fasteners as practically used in a joint, and accurately capture the three-dimensional stress states, material behaviour, bolt clamping, friction, secondary bending effects, load distribution as well as contact interactions between surfaces [18,19]. In addition, the localised damage in peak stress regions can reduce the laminates sensitivity to discontinuity. This results in highly conservative strength predictions based on initial failure around hole boundaries [20]. Hence the modelling must include the capability of progressive failure predictions. From current literature there is no work known to the authors that has included all the above factors.

This paper details 3D FEA to predict the static and fatigue strength of riveted, bonded and hybrid double lap joints made from thin carbon fibre/epoxy laminates. Multiple rivets with different array patterns were used in the riveted and hybrid joints. For the bonded and hybrid joints, the effects of two different types of bondline defects were also assessed. Nonlinear adhesive material property, rivet surface contact, friction forces and the Multi-continuum Theory (MCT) to simulate the progressive failure process are all included in the FEA models. The full load–displacement curve and failure mode for each joint configuration are also predicted. In addition the strain energy release rate (SERR) as a function of crack length for bonded and hybrid specimens are calculated to provide better understanding on how rivets affect the fatigue resistance of joints. The FEA prediction was compared with the results obtained in the experiment conducted by the authors which was reported in an earlier publication [8].

2. Methodology

Static and fatigue tests are conducted on eight different specimen configurations highlighted in Table 1.

The composite adherends are manufactured from HexPly M18/1/G939 carbon fibre prepreg [23] in a satin weave configuration with 0° and 90° fibres; Table 2. All specimens are made in a double lap joint configuration with the outer adherends five plies thick; [(0/90)/(45/−45)/(0/90)/(45/−45)/(0/90)] and the inner adherend ten plies thick; [(0/90)/(45/−45)/(0/90)/(45/−45)/(0/90)]s. Lap joints are known to produce severe stress concentrations around the ends of the overlap; to reduce this, the outer adherends are manufactured with a 5 mm long taper in the form of a ply drop as shown in Fig. 1. Adherends are cut using a water jet to a size of 120 mm × 57 mm. Specimens with six fasteners have a pitch distance of 16 mm [8]. The bond region is 50 mm × 57 mm and FM300-2K film adhesive is used with a nominal uncured thickness of 0.41 mm [24,25]; Table 3.

3. Finite element analysis setup

Abaqus CAE v6.13 is used to model the different configurations. A quarter of the specimen's geometry is modelled due to symmetry halfway across the width of the specimen and by making the assumption that the fasteners head and tail are the same, the model can be split midway through the thickness. Fig. 1 depicts the FEM models for the three main geometries. Table 4.

3.1. Model setup

The adherends were modelled using orthotropic material properties defined in Table 2. The adhesive was modelled using elastic-perfectly plastic material data specified in Table 3. A coefficient of friction of 0.1 was used between the fasteners and composite plate as well as between contacting plate surfaces [30,31]. This was applied using the master-slave algorithm with small sliding allowed between contacting surfaces and a neat fit between the rivets and the adherends.

A refined mesh using biased seeding was present around the fastener holes and at the ends of the overlap. A coarser mesh was used further afield from the overlap. Specimens containing an adhesive layer with no initial cracks had four elements placed through its thickness. A displacement was applied to the left end of the outer five ply thick adherend in the longitudinal (1) direction; Fig. 1. The right end of the middle adherend had a clamped boundary condition (u_1, u_2, $u_3 = 0$). A symmetry condition was also applied to the underside of the middle adherend and the plane halfway across the width of the specimen.

In order to accurately simulate the material failure behaviour, a micromechanical analysis method called the Multicontinuum Theory (MCT) provided by Autodesk as a commercial plugin to Abaqus was utilised [21,22]. Micromechanical analysis takes an additional step beyond the conventional laminate theory to separate the stress and strain in the matrix and fibre from a Representative Volume Element (RVE). MCT predicts failure at the fibre and matrix level by obtaining the volume averaged stress states in both the fibre and the matrix. Here, matrix failure is assumed to be influenced by all six of the matrix average stress components in a 3D analysis, whilst a quadratic function is used to find the average stress of the fibre [21,22]. In contrast progressive damage models such as the Hashin criteria provided by Abaqus can be computationally expensive and typically suffer convergence issues due to discrete stiffness reductions whilst not accounting for transverse stress and strain components which are accounted for in MCT. By implementing this method it allows modelling specimen behaviour with far greater accuracy than previously available. Due to this progressive damage model, fibre and matrix degradation values need to be found through an iterative process. In the riveted case, bearing failure is a compressive mode of failure, hence requiring slightly higher fibre and matrix degradation values. Optimal values ended up being 0.01 and 0.35 for the fibre and matrix respectively.

Table 1
Overview of thin double lap joint specimen configurations.

Bondline condition	Specimen	Joint type	No. rivets	Curing pressure (psi)	Rivet array
Pristine	Configuration 1	Hybrid	6	40.0	Square
	Configuration 2	Riveted	6	n/a	Square
	Configuration 3	Bonded	n/a	40.0	n/a
	Configuration 4	Hybrid	3	14.7	Staggered
Defective -2 mm Crack	Configuration 5	Bonded	n/a	40.0	n/a
	Configuration 6	Hybrid	6	40.0	Square
Defective – Semicured Bond	*Configuration 7	Bonded	n/a	40.0	n/a
	*Configuration 8	Hybrid	6	40.0	Square

* Specimens cured at 90 °C for 60 min in an autoclave.

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