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Static and fatigue testing thin riveted, bonded and hybrid carbon fiber double lap joints used in aircraft structures

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ABSTRACT

The static strength and fatigue resistance of mechanically fastened, bonded and hybrid double lap joints using relatively thin carbon fiber adherends have been experimentally investigated. The aim was to compare the static strength and fatigue resistance of a hybrid joint configuration consisting of both bonding and riveting, a purely riveted joint and a purely bonded joint. The effect of changing various parameters such as the mechanical fastener array configuration, rivet clamping pressure, bond strength, initial defects and curing conditions were also investigated.

No significant difference in the static strength of the bonded joints and hybrid joints was observed. However, the investigation showed that the fatigue resistance of a hybrid joint is superior to that of a bonded joint, particularly in the case where defects are present in the adhesive bondline; such defects may include cracking or an improperly cured bondline that would significantly reduce joint static strength and fatigue life.

The damage mechanism and failure mode in these three different joint configurations varied, ranging from bearing failure of the riveted joints through to tension failure in the hybrid joints. These were found to be controlled by the various parameters such as adhesive bond strength, clamping pressure and adherend bearing strength.

1. Introduction

The move toward light weight, high stiffness structures that have enhanced fatigue resistance and durability has led to the move from metal to composite structures. The damage mechanisms and failure modes in metal differ significantly than those in composites and hence further testing and analysis is required in understanding the behaviour of these materials and thus allow in devising new methods of achieving optimum structural efficiency.

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 been commonly used in the aerospace industry for many decades [1–3]. The ease of disassembling components and allowing for reliable inspection has been a great benefit. The key problem that arises through the use of mechanical fasteners is the high stress concentrations around the fastener holes which are much more severe in composite laminates compared to metal plates under the same loading condition. This is primarily due to the materials properties where metals are ductile and can yield [4].

Adhesively bonded joints are structurally more efficient than mechanically fastened joints as they perform better in distributing loads and hence eliminate a majority of high stress concentration problems seen in bolted joints. When conducting bonded repairs on structures, it is important to consider that the strength of the bond should not fall below that of the surrounding structure or the design ultimate strength of the structure. As such in the Aerospace Industry, strong ductile adhesives are used so that the loading capacity of the bond is significantly higher than the adherends for properly designed joints between thin members. Since adhesively bonded joints are strong in shear but weak in peel, the joints are designed so that the majority of the load is transferred in shear [4]. The quality of adhesively bonded repairs critically relies on the process control during the repair application. 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.

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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 [5]. In contrast to the mechanically fastened joint, the stress concentrations around the fastener holes is significantly reduced due to the presence of the adhesive layer which evenly distributes the load within the bond region. 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 [4,6–12] have investigated the behaviour of hybrid joints. Initial failure in all types of hybrid joints is predominantly due to debonding. Sun et al. [7] showed how the use of ‘attachments’ can allow fasteners to carry more load in a hybrid joint configuration. Hart-Smith [8] 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. Kelly [9] investigated the load distribution in hybrid joints with a single bolt using finite element analysis. It was concluded that increasing adherend thickness and adhesive thickness increases load transferred by the bolt; whilst increasing overlap length, pitch distance and adhesive modulus has the opposite effect.

Thus far a majority of research has focused on developing numerical models; however there is little published work on experimental investigations, more so fatigue testing in the field of hybrid composite lap joints. The methods in which multiple fasteners interact with each other, how adhesive bond quality affects joint strength and the influence of initial defects are all important questions that need to be answered. Through the static and fatigue tests conducted, this paper aims at answering these questions and alongside this tailoring the results towards aerospace applications through the use of aerospace grade fasteners, adhesives and carbon fiber laminates.

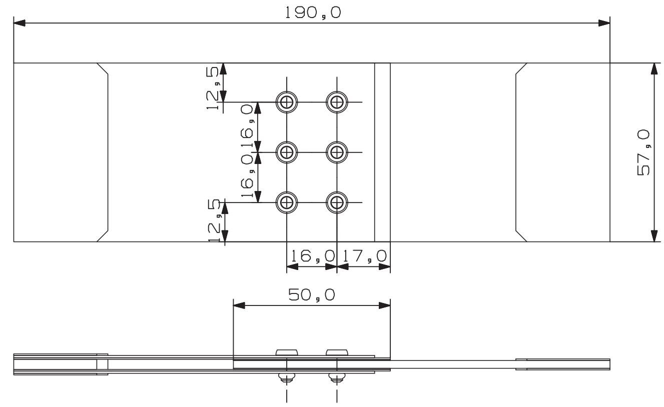

Fig. 1a. Dimensions (mm) for a specimen containing 6 fasteners in a square array.

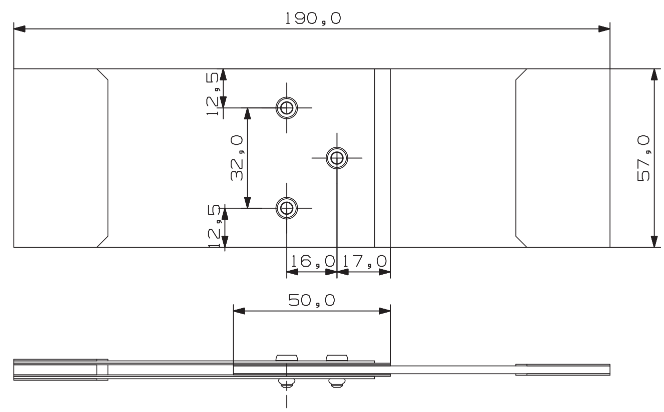

Fig. 1b. Dimensions (mm) for a specimen containing 3 fasteners in a staggered array.

2. Experimental setup

Thin riveted specimens, bonded specimens and hybrid specimens in a double lap joint configuration were static and fatigue tested to determine their relative strengths. Specimens comprising of rivets (Cherry MaxiBolt CR7621U-05-04) have either a square array configuration (6 rivets) or a staggered array configuration (3 rivets) commonly found in aircraft structures. The pitch and transverse pitch distance of a staggered rivet array configuration is typically 8D and 4D respectively, (where ‘D’ represents rivet diameter). Due to the finite width of the specimen a square array was selected to have a pitch and transverse pitch distance of 4D. General fastener spacing in metal and composite structures can be found in [13,14]. Note that only two rows of rivets were looked at; this is widely used in aircraft structures and known to be the most efficient rivet pattern. In the case of bonded specimens, the bondline quality was checked through Ultrasonic A-Scanning using an Epoch XT scanner with a 5 MHz probe.

2.1. Materials

The composite adherends where manufactured from HexPly M18/1/G939 carbon fiber prepreg [15] in a satin weave configuration with 0° and 90° fibers, Table 1. This investigation is focused on the performance of thin adherends. All specimens were made in a double lap joint configuration with the outer adherends 5 plies thick with a stacking sequence of [(0/90)/(45/−45)/(0/90)/(45/−45)/(0/90)] and the inner adherend 10 plies thick with a stacking sequence of [(0/90)/(45/−45)/(0/90)/(45/−45)/(0/90)]s. Lap joints are known to produce severe stress concentrations around the end of the overlap, hence to reduce this the outer adherends were manufactured with a 5 mm long taper in the form of a ply drop as shown in Fig. 1. Adherends were cut using a water jet to a size of 120 mm × 57 mm. The bond region was 50 mm × 57 mm and FM300-2 K film adhesive manufactured by Cytec Engineering [17,18] was used with a nominal uncured thickness of 0.41 mm, Table 2. Proper surface preparation plays a fundamental role in achieving high bond strength. The bond region for the relevant adherends were first abraded using ScotchBrite 7447 followed by degreasing using MEK then blasted with 50 micron diameter aluminium oxide grit with excess grit removed with high pressure nitrogen gas.

With a total specimen thickness of ~5 mm, Cherry MaxiBolt CR7621-U05-04 rivets 4.16 mm in diameter were used as the mechanical fastener. These rivets are well suited to aerospace

Table 1
Elastic properties for HexPly M18/1/G939 carbon fiber prepreg; [15,16].

	E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	G_{13} (GPa)	ν_{12}	Tensile strength			Compressive strength	
						$+S_{11}$ (MPa)	$+S_{22}$ (MPa)	S_{12} (MPa)	$-S_{11}$ (MPa)	$-S_{22}$ (MPa)
M18/G939	65	67	4.0	4.0	0.04	800	800	100	800	800