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Development of design allowables for the design of composite bonded double-lap joints in aerospace applications

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ABSTRACT

This paper describes progress towards developing design guidelines for a number of composite bonded joints in aerospace applications. The premise of a universal failure criterion is impractical given the number of adherend-adhesive configurations and layups available. However, for a finite number of joint configurations, design rules can be developed based on experimental test data and detailed finite element (FE) modelling. By using these techniques rather than the traditional overly conservative knock down factors, more of the performance of composite bonded joints can be accessed. The work presented here experimentally studied the effect of the substrate layup, adhesive type and adhesive thickness on double-lap joint (DLJ) strength. The corresponding failure surfaces were analysed and failure modes identified. Following this, detailed FE models were developed to identify the trends associated with altering joint parameters. Finally, the stresses and strains within the adhesive and substrate were analysed at the joints respective failure loads to identify critical parameters. These parameters can provide an insight as to the stress state of the joint at failure or near failure loads, and hence its true performance.

1. Introduction

The use of composite materials has grown significantly in recent years resulting in a demand for updated design protocols which better capture their performance. Adhesive bonding as a joining mechanism is used extensively, primarily due to the reduced mass penalty and more uniform distribution of load compared to mechanically fastened joints. Despite substantial research in the field, reliable failure criteria that can be used across multiple composite bonded joint configurations remains problematic [1]. Fibre reinforced plastic (FRP) bonded joints are inherently difficult to model due to the complex combination of potential failure modes present.

Early analytical investigations concerned with the mechanical response of bonded joints were developed by Volkersen [2] and Goland and Reissner [3]. Volkersen introduced the concept of differential shear. Goland and Reissner were the first to consider the effects of eccentric load paths and to include the adhesive peel stress. Several researchers have since contributed to the refinement of closed-form solutions, most notably Hart-Smith [4,5]. Da Silva et al. [6] presented a summary of the development of classical closed-form techniques since Volkersen.

Due to the maturity of the field, a significant amount of literature exists examining the behaviour of bonded joints. Single-lap joints (SLJ) and double-lap joints (DLJ) are commonly discussed in literature due to their widespread use in industry. However, variations of the traditional lap design have been heavily investigated in recent years by several authors due to their potential performance benefits. Most notably, Avila and Bueno (2004) investigated the novel design of a 'wavy' bonded joint using both numerical and experimental methods. They observed an increase in joint load bearing capacity of approximately 41% when compared to traditional SLJs of similar design [7].

Several researchers have also investigated the influence of varying joint parameters on composite bonded joint strength [8]. In these studies, researchers have investigated the effect of bonded surface preparation, adhesive thickness, spew fillet, adherend stacking sequence, adherend ply angle, environmental conditions etc. [9,10]. Banea and da Silva provide a useful review on the aforementioned influences on bonded joint performance [11]. Kanerva and Saarela [12] studied the effect of peel ply surface treatment against plasma and blasting treatment for composite adherends. The authors found that while peel ply treatment does increase surface free energy compared to untreated substrates, the use of plasma or mechanical abrading treatments provide greater bond strength [12]. Belingardi et al. [13] investigated the effect of the spew shape and size on adhesive stresses in adhesive joints.

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Peak stresses were found to be dependent on the size and shape of the spew fillet, Hence, careful consideration of spew fillet shaping can significantly reduce stress concentration [13]. Environmental factors are equally important factors when designing joints. The main environmental factors to consider are temperature and humidity, both in operation and manufacturing[14]. Exposure to climates outside the design specification can lead to permanent chemical and physical changes to the adhesive. Parker [14] studied the effect of adverse environmental conditions on CFRP bonded joints. The study showed that exposing dried laminates to humid environments prior to bonding can be detrimental to joint performance [14]. Meneghetti et al. [15] studied the failure mechanisms associated with fatigue damage in composite bonded joints. The authors placed emphasis on the effect of surface ply orientation, stacking sequence, adhesive fillet geometry and overlap length. The authors observed failure to initiate at the adhesive-adherend interface with 0° surface plies. Failure progresses into the subsequent 90° layer leading to multiple inter/intralaminar failure paths [15].

Recently, research in this field makes use of complex techniques, employing cohesive zones or ductile damage material models to accurately predict the progression of failure in composite bonded joints [16]. These techniques are favoured over traditional failure criteria as researchers note the former offer less precise predictive capabilities [17]. Complicated failure criteria do exist, however, a considerable amount of experimental work is necessary before they can be deemed universal. In an industrial setting, complex and time-consuming techniques are not suitable where rapid prediction is required. Hence, engineers within industry may compensate for modelling uncertainties associated with simplified modelling techniques [18].

Given the lack of fast and reliable composite bonded joint design tools, the following work aims to develop a novel methodology for identifying the performance of composite bonded joints in aerospace applications. The novelty in the work presented lies in the way in which relatively simple techniques can be consolidated to achieve a significant improvement in performance for a select number of composite bonded joints. While complex damage models are improving in terms of industrial applicability, they are not yet practical given the additional material data needed to conduct such analyses and the time penalty associated with non-linear modelling. Thus, in an industrial context, the approach adopted in this study was considered the most efficient and cost effect solution. The simple modelling techniques facilitate the rapid analysis requirement by maintaining simple linear-elastic modelling techniques (and avoiding complex non-linear damage models), whilst introducing improved design allowables.

Section 2 investigates the effect of adhesive modulus, substrate stiffness, substrate architecture and adhesive thickness on joint performance. Section 3 describes the development of detailed finite element models used to identify trends in stresses and strains associated with manipulating joint configuration. Section 4 uses the detailed numerical models to identify critical parameters at which failure is known to occur. 'Safe' values are also identified which confidently predicts a stress at which the material remains undamaged. Finally, the key outcomes and failure criteria developed from this study are summarised.

2. Experimental study

2.1. Method and materials

To develop more robust predictive techniques, an array of experimental work must first be carried out, which evaluates the real performance of various joint configurations. In this study, composite double-lap joints (DLJ) of varying composite substrate materials and layups and adhesive thicknesses and materials were investigated. The test programme was selected based on a commonly used joint configuration in the aerospace industry. All tests were carried out at room temperature in ambient conditions. The structural joints detailed in this study are designed to withstand the initial launch phase of a satellite into orbit. These structural components are typically shielded from the external environment. Consequently, environmental factors such as temperature and humidity are not the main focus of this study.

Each specimen was manufactured and tested to ASTM D3528-96 specifications, these being a nominal overlap length of 12.9 mm and joint width of 25.4 mm. Substrates are required to be cut from a single 300 × 300 mm CFRP panel as per the ASTM standard, to minimise variances that may be introduced from manufacturing multiple panels. The CFRP substrates were surface prepared using the glass-bead abrasion technique followed by a water-break test to ensure the surface has been adequately prepared for bonding. All adhesive fillets were controlled using PTFE rods of 2 mm diameter. The bondline thickness was controlled using bondwire placed between each specimen, which were then removed during the cutting process.

Two common aerospace carbon fibre reinforced plastic (CFRP) prepregs were used. The first consisted of an epoxy resin matrix system (MTM44-1) and intermediate modulus fibres (IMS65). The second, a cyanate ester resin system (HTM143) and high-modulus fibres (M55J). The prepreg woven plies consisted of a 2 × 2T architecture. The structural adhesives were purposely chosen due to their distinctly different mechanical properties (3 M 9323-low modulus, EA 9394-high modulus).

All tests are conducted under carefully controlled loading and

Table 1
DLS test programme.

	Substrate			Adhesive	
Config.	**Layup**	**Thickness (mm)**	**Material**	**Adhesive material**	**Thickness (mm)**
Test A	$[0/45/90/45/-45/0/45/90]_s$	2.05	Low modulus quasi-isotropic with surface ply orientated in the 0° direction	EA 9394	0.25
Test B	$[90/45/0/45/-45/90/-45/0]_s$	2.05	Low modulus quasi-isotropic with surface ply orientated in the 90° direction	EA 9394	0.25
Test C	$[W/0/45/90/45/-45/0/-45/90]_s$	2.46	Low modulus quasi-isotropic with 0/90° woven surface ply	EA 9394	0.25
Test D	$[0/45/90/45/-45/0/45/90]_s$	1.84	High modulus quasi-isotropic with surface ply orientated in the 0° direction	EA 9394	0.25
Test E	$[90/45/0/45/-45/90/-45/0]_s$	1.84	High modulus quasi-isotropic with surface ply orientated in the 90° direction	EA 9394	0.25
Test F	$[W/0/45/90/45/-45/0/-45/90]_s$	2.26	High modulus quasi-isotropic with 0/90° woven surface ply	EA 9394	0.25
Test G	$[W/0/45/90/45/-45/0/-45/90]_s$	2.46	Low modulus quasi-isotropic with 0/90° woven surface ply	3 M 9323	0.25
Test H	$[W/90/45/0/45/-45/90/-45/0]_s$	2.46	Low modulus quasi-isotropic with 0/90° woven surface ply	EA 9394	0.40