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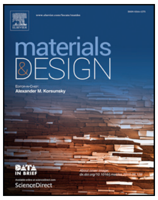

Ply-overlap hybrid technique for joining dissimilar composite materials

Jasim Ahamed [a], Mathew Joosten [a], Paul Callus [b], Michael R. Wisnom [c], Chun H. Wang [a,*]

[a] Sir Lawrence Wackett Aerospace Research Centre, School of Engineering, RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia
[b] Aerospace Division, DST Group, Melbourne, Australia
[c] Advanced Composites Centre for Innovation and Science, University of Bristol, Queen's Building, University Walk, BS8 1TR Bristol, UK

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ABSTRACT

Hybridisation of multiple materials is emerging as a key strategy to achieve high performance lightweight structures while keeping the cost low. Fundamental to creating strong and cost-effective hybrid composites is the ability to efficiently join dissimilar materials. Herein we present a novel co-curing ply-overlap joint technique for integrating dissimilar composite materials. Experimental studies are conducted to identify the dominant failure mechanisms and the effect of design parameters, such as the spatial distances between ply terminations and overlap length, on the strength of hybrid composite ply-overlap joints. To enable optimisation of ply-overlap joints, analytical and computational models are developed and validated against the experimental data. The results demonstrate that ply-overlap joints are capable of approaching the un-notched strength of the glass composite material. The validated predictive tools enable design optimisation of hybrid composite structures.

1. Introduction

Integration of multiple materials enhances design flexibility and enables the optimal utilisation of materials with different properties to create affordable high-performance structures meeting diverse functional requirements [1]. Most common examples of such multi-material hybrid structures combine metals with advanced composite materials and can be found in large aircraft structural assemblies [2], ship hulls [3], automotive drive shafts [4] and bridge decks [5]. Hybrid structures combining dissimilar composite materials are also required for both structural and non-structural functions. For example, structural repair of a composite structure may be conducted with another composite material of dissimilar stiffness and strength [6]. Another application which requires joints between dissimilar composites is multifunctional carbon fibre-reinforced plastic (CFRP) aircraft skin structures with an electrically insulating (dielectric) window fabricated from dielectric composites such as glass fibre reinforced plastic (GFRP) or quartz fibre reinforced Plastic (QFRP) to allow the transmission and reception of radiofrequency signals [7–9]. Fig. 1 shows an example of such multifunctional load-bearing antenna structure. One simple design approach is to assume that the dielectric window (denoted as radar transparent window in Fig. 1) does not carry any load and is treated as an open hole. In applications where the dielectric window is larger than the typical 6.35 mm diameter open hole used in aerospace design, significant local reinforcement around the dielectric window is required to ensure the structure can sustain the design loads. For example, the size of a half-wavelength slot antenna for X-band (8–12 GHz) applications ranges between 18.75 mm and 12.5 mm. The residual strength of an open hole within this size range will be substantially less than that pertinent to 6.35 mm diameter hole; therefore the aperture will need to be stiffened to meet the design ultimate strength requirement. This additional reinforcement around the dielectric window may be reduced, or eliminated entirely, by forming a co-cured hybrid joint of sufficient strength to carry the design loads.

Joining dissimilar composite materials requires careful design to maximise joint strength as the differing thermal and mechanical properties can affect the load carrying capacity of the joint. Co-curing is preferred over mechanical fastening or post-cure adhesive bonding for joining dissimilar composites as they offer higher structural efficiency and lower manufacturing cost. A number of co-cured ply joining techniques have been proposed in the literature [10,11–13,14,15]. The simplest technique is to butt individual plies by intelligently tailoring the positions of the ply terminations. Baucom et al [10] investigated several ply joining techniques for unidirectional CFRP laminates and found that the spatial distribution of ply terminations and the distance between adjacent ply terminations had a significant influence on the joint strength. Similar techniques were employed to efficiently transition from hybrid CFRP/titanium laminate to CFRP laminate for bolted joint applications [11–13]. For the load-bearing antenna applications, it is necessary to terminate all conductive CFRP plies outside the dielectric window for antenna requirements. Moreover, the introduction of a butted ply termination reduces the laminate strength by 35% [14]. The strength of an interleaved scarf joint, where the ply terminations are aligned along a linear scarf, between carbon fibre laminate and glass

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[*] Corresponding author.
E-mail address: chun.wang@rmit.edu.au (C.H. Wang).

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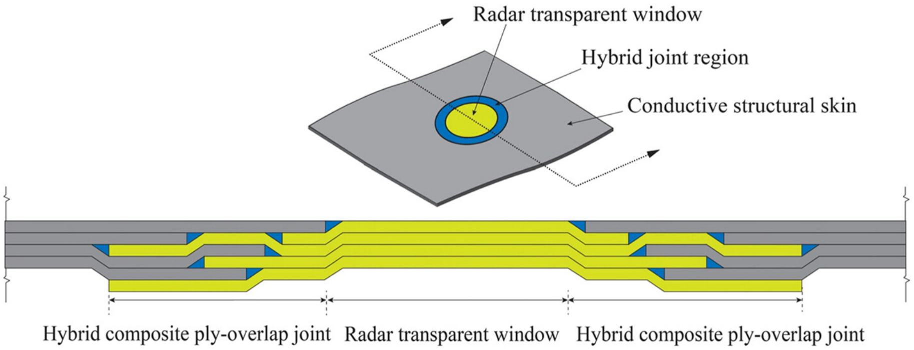

Fig. 1. Multifunctional load-bearing antenna structure using hybrid composite ply-overlap joint.

fibre laminate was found to be 31% lower than the un-notched strength of the glass fibre composite [15].

The aim of the present work is to develop a new joining technique to achieve higher joint strengths than ply-interleaved joints that have been recently reported by the present authors [16]. An example of the new joining technique, denoted as the ply-overlap joint, is shown in Fig. 1. It should be noted that this type of joint has been developed specifically for use with integrated load bearing antenna structures. The structural behaviour of a number of ply-overlap joints is evaluated experimentally. Both analytical and finite element models are employed to predict ultimate joint strength. The work presented herein is outlined as follows. Section 2 discusses the key joint design considerations and describes the ply-overlap joint configurations. Details of the experimental program including manufacturing and testing of representative joint specimens, and the test results are provided in Section 3. Two modelling techniques used to predict joint strength are described in Section 4: analytical pull-out models based on delamination fracture theory and finite element models employing cohesive damage mechanics. This is followed by a discussion of the key findings and application to load-bearing antennae in Section 5. The main conclusions of this study are summarised in the final section.

2. Joint design

2.1. Design considerations

The primary function of the hybrid joint considered in this work is to transfer loads efficiently between the CFRP structural skin and the GFRP dielectric window. To avoid unnecessary structural reinforcement surrounding the dielectric window, the joint strength must exceed the minimum of the design allowable strengths of the CFRP skin and the GFRP dielectric window.

Achieving maximum load transfer between the dissimilar composite plies requires careful determination of the various design parameters. For a generic hybrid composite construction composed of dispersed overlaps between carbon and glass plies (Fig.2), these parameters include the carbon and glass ply orientations (θ_i^c and θ_i^g) respectively, the overlap length (l_i), and the spatial distribution of the overlaps or joint geometry. The locations of resin pockets are denoted by x_i, with the subscript i corresponding to the ply index. The overall joint length, L, is a function of the overlap length and joint geometry. The taper angle of the overlap region can be kept constant provided the overlaps are offset as shown in Fig.2. The ply-overlap technique, however, produces an undesirable increase in laminate thickness in the joint region. Ideally the joint geometry should be designed to be symmetric and flush, if possible, in order to minimise bending when the structure is loaded under compression, which can lead to high peel stresses. In addition to the mechanical considerations, thermal residual stresses caused by the different coefficients of thermal expansion of carbon and glass composites must also be accounted for in the design. The key design challenge is then to achieve strength equal to or greater than that the design allowable strength of GFRP laminate, which is typically the open hole tension or compression strength, while minimising joint length and overlap thickness.

2.2. Joint concepts

In the current study three ply-overlap design configurations are proposed for joining quasi-isotropic CFRP and GFRP laminates as shown in Fig. 3. The simplest technique is to overlap every ply, with all plies being terminated at the same location as shown in Fig. 3(a). This design configuration, which will be referred to as aligned-overlap, requires the shortest joint length but produces an undesirable abrupt thickness change: the thickness of the overlapped region is equal to the sum of the thicknesses of the two laminates. Alternatively, the overlaps can be staggered analogous to a double scarf as shown in Fig. 3(b). The staggered-overlap joint requires a comparatively long joint length but the taper angles of the overlap region are minimised. The third configuration, shown in Fig.3(c), produces a flush joint which is designed by selectively overlapping the main load-bearing plies aligned with the loading direction, while terminating the same number of weaker off-angle plies outside the joint region. In the flush-overlap configuration shown in Fig.3(c) for a layup of $[45/0/-45/90]_{2s}$, the 0° glass plies are overlapped with 0° carbon plies and ±45° glass plies are simply abutted

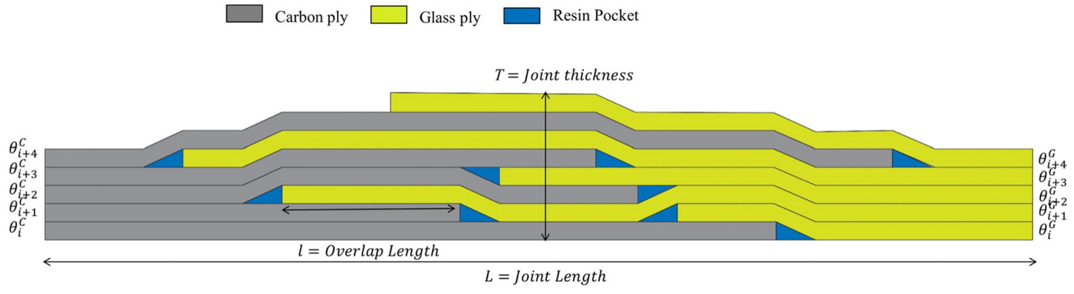

Fig. 2. Hybrid composite ply-overlap joint design parameters.