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Ply-interleaving technique for joining hybrid carbon/glass fibre composite materials

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Efficiently joining materials with dissimilar mechanical and thermal properties is fundamental to the development of strong and lightweight load-bearing hybrid structures particularly for aerospace applications. This paper presents a ply-interleaving technique for joining dissimilar composite materials. The load-carrying capacity of such a joint depends strongly on several design parameters such as the distance between ply terminations, the spatial distribution of ply terminations, and the stiffness and coefficients of thermal expansion of the composites. The effects of these factors on the strength of quasi-isotropic hybrid carbon/glass fibre composite are investigated using combined experimental, analytical and computational methods. Through fractographic analyses significant insights are gained into the failure mechanism of the hybrid joints, which are then used to aid the development of predictive models using analytical and high fidelity computational methods. To characterise the interaction between transverse matrix cracking and delamination, continuum damage mechanics model and cohesive zone model are employed. The predictions are found to correlate well with experimental data. These modelling tools pave the way for optimising hybrid joint concepts, which will enable the structural integration of dielectric windows required for multifunctional load-bearing antenna aircraft structures.

1. Introduction

High performance load-bearing joints are fundamental to the application of affordable lightweight composite structures in a wide range of industries. Owing to the anisotropy and the complexity in failure mechanism of fibre-reinforced composites, joining them is a major challenge, particularly for material systems with different mechanical and thermal properties. In the fabrication of composite structural assemblies for automotive, naval and aerospace applications, multiple materials with different properties are employed for minimising cost and weight to optimise performance. The use of multiple materials is also driven by the need to satisfy additional functional requirements, such as reception and transmission of radar signals [1].

Of particular interest to this study is multifunctional load-bearing antenna [1–3] which integrates a carbon fibre composite structural skin, which is electrically conductive, with an electrically insulating, radar transparent window fabricated from dielectric composite materials such as glass or quartz fibre composite. A schematic illustration of this hybrid composite load-bearing antenna is shown in Fig. 1(a). One method of achieving efficient load transfer between the dielectric window and the conductive structural skin is to interleave the composite plies. An example of this co-cured joining method, referred here as ply-interleaving, is illustrated in Fig. 1(b). To achieve high structural strength of the load-bearing antenna it is necessary to optimise the design, such as the step lengths of interleaving plies and the spatial distribution of the ply termination locations, because the ply terminations are accompanied by resin rich zones or resin "pockets" and discontinuities with strong corner singularities that can give rise to delaminations. Recent studies have investigated the delamination behaviour at ply terminations in unidirectional [4], quasi-isotropic [5], and also in discontinuous carbon fibre reinforced plastics (CFRP) laminates [6] by introducing "ply cuts" or "slits" in prepregs. Work has also been published on unidirectional hybrid carbon/glass fibre composite laminates [7,8]. These studies have shown that joint topological features such as the distance between adjacent ply terminations, spatial distribution of ply terminations, and laminate stacking sequence strongly influence the failure mechanism and ultimate strength. Baucom et al. [9] investigated several co-cured joining techniques for unidirectional CFRP laminates. In the work on hybrid CFRP/titanium bolted joints [10–12],

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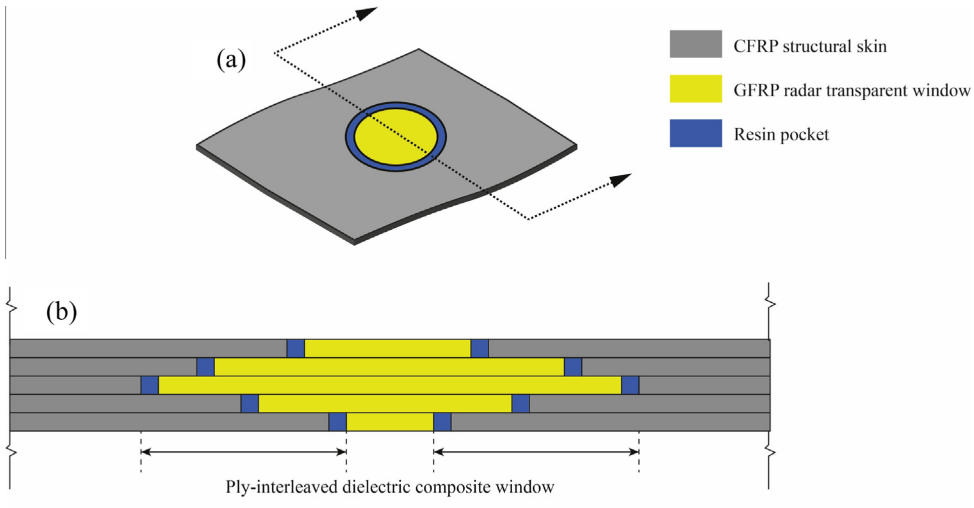

Fig. 1. Structurally integrated RF window for CFRP load-bearing antenna structure using a ply-interleaved joining technique. (a) Schematic of load-bearing antenna. (b) Cross-section of antenna. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

co-curing methods were developed to efficiently transition from hybrid laminate to CFRP laminate. High strength was achieved in the transition region by tailoring the positions of the carbon ply-titanium foil terminations while keeping 0° plies continuous. For load-bearing antenna applications requiring a radar transparent aperture, it is necessary to terminate all conductive CFRP plies outside the dielectric window, typically made of glass fibre reinforced plastics (GFRP), for antenna requirements. However, current literature does not address how the ply-interleaving technique could be applied to joining dissimilar fibre reinforced composites.

In this paper, we present novel ply-interleaving techniques for joining quasi-isotropic dissimilar fibre-reinforced polymer composites. Specifically, the objectives of this study are to (1) investigate the failure mechanisms and the influence of key design parameters and (2) develop an analysis methodology for joint strength prediction. The work presented herein is outlined as follows. In Section 2, the key joint design considerations are described and a number of candidate structural concepts for hybrid ply interleaved-joints are proposed. Details of the experimental program including manufacturing, testing and discussion of key results are provided in Section 3. The analytical and computational modelling approaches for strength prediction are described in Sections 4 and 5 respectively. The analytical approaches are based on strength of materials and linear elastic fracture mechanics approaches while computational modelling employs continuum damage mechanics and cohesive element method to accurately predict the onset and growth of delamination and matrix damage. The predictive capability of the two analysis approaches are compared and discussed in Section 5. Finally, an application of the ply-interleaving method to structurally integrate load-bearing antennas is presented to demonstrate the potential benefits of the new joining technique.

2. Ply-interleaved hybrid composite joints

2.1. Joint design considerations

A generic laminate lay-up of a ply-interleaved hybrid carbon/-glass composite joint is shown in Fig. 2. The carbon and glass plies are shaded in black and yellow respectively. The locations of resin pockets (shaded in blue) at ply terminations are denoted by x_i, with the subscript i denoting the ply index. The structural performance of the joint depends on a number of design parameters such as ply orientations of the carbon (θ_i^C) plies and the glass plies (θ_i^G), step length (l_i), and the spatial distribution of the ply terminations.

Resin pockets formed at the ply terminations act as delamination initiation sites due to the presence localised stress concentrations and the low strength of the matrix relative to the fibres. The resin pocket size must be minimised by abutting the carbon and glass ply, as large resin pocket size can lead to significant degradation in strength [4,9]. Also, stress concentrations from neighbouring resin pockets can interact if the step length is below a certain critical value. This critical step length varies with the properties of the material surrounding the resin pocket [4,9,13,14]. The stress concentration at ply terminations is also influenced by the orientation of the carbon and glass plies with respect to the loading direction. Joint length represents the total length of the hybrid region and is dependent on the joint configuration and step length. In bonded joints, increasing the joint length typically increases the strength almost linearly up to certain length known as the transfer length and approaches an asymptotic value [15]. Selecting an optimal joint configuration is necessary to maximise load transfer while keeping the overall joint length at the minimum. Employing a balanced laminate configuration can alleviate secondary bending effects caused by the presence of material discontinuities at ply terminations. In addition to mechanical considerations, the differences in the coefficient of thermal expansion between carbon and glass fibre composites may produce residual thermal stresses/strains which must be accounted for in the design.

2.2. New structural concepts

A number of joint configurations are feasible by tailoring the design parameters for a given loading condition and combination of materials. The focus of this study is to develop a flush joint concept, where there is no significant change in the thickness in the joint region, for joining dissimilar quasi-isotropic carbon and glass fibre composite laminates. Previous studies [9–11,16] have indicated that the high strength can be achieved using interleaved-scarf and finger joint configurations, while maintaining a constant joint thickness. The interleaved-scarf joint is produced by offsetting successive ply terminations in opposing directions along the length of the joint while retaining symmetry about mid-plane, as shown Fig. 3(a). This concept produces a gradual reduction in stiffness from carbon to glass laminate. Baucom et al. [9,10] showed that interleaved-scarf joint configuration can achieve high strength for unidirectional carbon fibre composite laminates. For finger joints, the positions of the 0–0° ply terminations are staggered in the thickness direction, referring to Fig. 3(b). Several variations of