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An analysis of the effect that global taper ratio variations have upon compressively loaded asymmetric non-crimp fabric laminates incorporating realistically modelled transverse tapers

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A B S T R A C T

Finite Element Analysis of transversely tapered [0/90] non-crimp fabric (NCF) representative of realistic laminate wing covers subjected to compressive loading was undertaken. The main objectives were to determine the effect on laminate stress distribution of contesting existing global taper ratio heuristic guidelines of 20:1. Positive challenge of these guidelines is seen as an enabler of mass reduction and therefore subsequent potential commercial gains. The laminates studied consisted of a 48-ply thick section and a 32-ply thin section comprised of 0.25 mm thick NCF carbon/epoxy lamina. This configuration characterised a 12 mm–8 mm reduction in thickness creating a case which was structurally representative of the taper arrangement commonly associated with aircraft wing covers. The geometry of the laminate was created with a global taper ratio of 20:1 analysed and subsequently re-modelled and re-analysed with a global taper ratio of 10:1. A number of surveys were undertaken on the Finite Element Model both holistically across the laminate and in detail at the ply drop locations and these investigations failed to highlight significant increases in stress as a result of reducing the global taper ratio. The work undertaken suggests that a decrease in global taper ratio is possible without noticeable increase in associated stress and this could enable 50% reductions in mass in the taper region of composite structures to be realised in an ever marginalised mass receding opportune environment.

1. Introduction

Tapered laminates are incorporated extensively in aircraft composite structures as a means of tailoring the structural strength to meet the applied loads. The laminate is tapered by terminating plies and these resulting terminations often create stress concentrations which can lead to laminate failure at a load below that tolerable by the thin section.

An area where substantial composite structures are encountered is aircraft wing covers. These covers on large commercial aircraft are subjected to significant loading and are therefore sizeable structural items. As a result changes to their design can help realise mass reduction of a magnitude worth exploring. The ratio of the dropped length to the dropped thickness is known as the global taper ratio and existing empirical guidelines suggest that a ratio of 20:1 should be adopted for transverse tapers, this form of tapering is frequently employed. Mass reductions of aircraft structures are likely to become increasingly marginalised and any opportunity to reduce mass from commercial and environmental perspectives must be explored. Therefore opportunity to challenge the global taper ratio guidelines with a potential to realise mass reductions, thereby improving aircraft fuel efficiency, must be considered. Boeing [1] predict a significant rise in aircraft travel in the forthcoming twenty years and therefore a subsequent requirement for a substantial demand for new aircraft is driving materials and manufacturing processes to raise production rates to satisfy these demands and the use of non-crimp fabric (NCF) employing resin infusion techniques are seen as potential methods for meeting these manufacturing rate demands.

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2. Method

2.1. Tapered laminates

Tapered laminates are classed in the following categories, internal, external, symmetric (mid-plane) or asymmetric and longitudinal or transverse. Transverse tapers are found perpendicular to the main load direction, whilst longitudinal tapers run parallel to the primary load direction and therefore transverse tapers are more structurally critical than longitudinal tapers. Many applications, for example, where smooth aerodynamic profiles such as aircraft wing covers are required on one surface, prevent the use of symmetric ply drops and asymmetric tapering is therefore required whilst transverse taper ratios are more frequently employed and more critical than longitudinal taper ratios. For these reasons asymmetric laminates incorporating transverse tapers are more commonly studied due to their extensive engineering applications as is the case in this paper. Fig. 1 details the geometry and main terms associated with tapered laminates.

2.2. Tapered laminate ply drop configuration

A number of studies have been undertaken employing numerical, analytical and experimental studies of the failure of tapered laminates and some, as a result of their findings, have produced design guidelines on the drop configuration this is aimed at improving the delamination resistance of the laminate. Fish and Lee [2], NASA [3], Paul et al. [4], ESDU [5], Mukherjee and Varughese [6], Dhurvey and Mittal [7], Vidyashankar and Murty [8] all, in varying degrees, offer guidance on the order and position in the laminate in which plies should be terminated to reduce the likelihood of tapered laminate failure. Whilst the objective of this study is to challenge the conservatism of the existing guidelines in relation to global taper ratio, it provides, based on the findings of previous studies, an initial position from which to ensure that the likelihood of success is heightened. The ply drop configuration adopted in this paper is based on the existing guidelines and is shown in Appendix A.

2.3. Global taper ratio

The global taper ratio defines the transition rate from the thick section to thin section of a tapered laminate and common heuristic guidelines are provided by NASA [3] and Thomas and Webber [9] who suggest that a ratio of 20:1 should be adopted in transverse tapers. The intention of this study is to challenge the 20:1 ratio with a target ratio of 10:1 accepting that greater taper

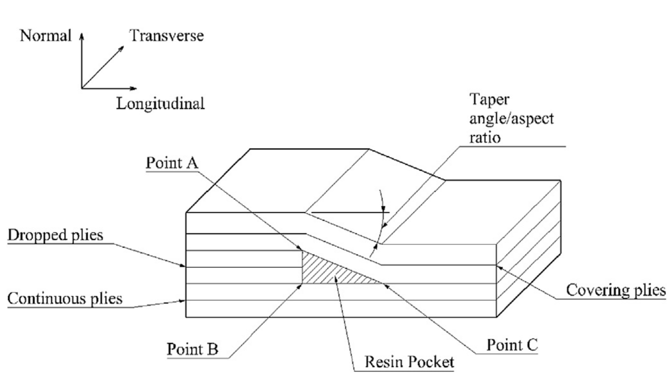

Fig. 1. Tapered laminate geometry terminology.

ratios, e.g. 12:1 may require to be investigated if the study highlights significant variations in stress as a result of the incorporation of the 10:1 design. The reduction in section for this study, which reflects realistic aircraft wing skin geometries, corresponds to a reduction in thickness of 4 mm. This, following existing design rules, leads to a taper length of 80 mm whilst the taper ratio of 10:1 results in a taper length of 40 mm, both of these geometries will be modelled and analysed. He, Hoa and Ganesan [10] elucidate that delamination prediction is dependent on the accurate prediction of the interlaminar stresses, initial delamination location prediction and accurate simulation of the delamination growth. In addition Thomas and Webber [9] state that the high interlaminar stresses found in tapered laminates may initiate delamination. Furthermore Wilkins [11] identified ply drops as discontinuities and therefore act as stress concentration locations whilst Varughese and Mukherjee [12] highlight that these discontinuities formulate interlaminar stresses, leading to premature laminate failure thereby removing advantages that ply drops provide as a result of the strength reduction they create.

Classic laminate theory (CLT) provides fairly simple means for calculating stress and strain in laminates and is in essence a plane stress analysis. It does not account for three-dimensional stresses at free edges which must be present for boundary equilibrium. Kim and Mai [13] state that the local stresses near ply drops may be out of plane even if the remote loading is in plane and Kim, Rhee and Cho [14] highlight that the stress concentrations near a dropped ply are similar to that at a free edge. Most commonly in previous studies, Finite Element Analysis has been undertaken to address the complex geometrical problem which tapered laminates present. He, Hoa and Ganesan [10] in their review of tapered laminate publications described the two methodologies used to determine the delamination onset and propagation via stress-strength and fracture mechanics approaches. This study compares the stress magnitude and distribution for each of the two taper ratio models.

2.4. Local drop geometry

Curry, Johnson and Starnes [15] studied unidirectional tape and noted the resin pocket created at the end of the drop ply, as shown in Fig. 1. In addition they noted the change in geometry of the 90° ply under vacuum forming. They further noted that the 90° ply was deformed by the covering ply 0° and migrated into the transition region from the original thickness to the new drop thickness. Regardless of this discovery, they chose to model this drop geometry with ply deformation as is shown in Fig. 1. Carella-Payan, Kawashita and Allegri [16] also observed a similar phenomenon and further noted that this reduced the taper angle, but also chose not to reflect this geometry in their Finite Element Model. As a result of this information, micrograph specimens were produced and examined to confirm the previous findings. Fig. 2 endorses the observations of the other studies and reveals the extent of the 90° ply migration into the resin pocket, where the 90° ply is on the vacuum bag side of the 0° ply. Close inspection of Fig. 2 shows the 0/90° biaxial NCF with the 0° dropped ply closely resembling the common method of geometry depiction, whilst the 90° ply above deforming allowing the covering ply above to transition more gradually across the ply drop region. Fig. 3 details the effect when the 0° ply is on the vacuum bag side of the 90° ply. In this example the 0° ply deforms over the 90° which itself deforms, once again allowing the covering plies above a smoother and shallower transition across the ply drop region. Both of these scenarios were modelled, complete with resin pocket shown in red (in the web version), as