Composite Structures 146 (2016) 26–33

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Resin treatment of free edges to aid certification of through thickness laminate strength

Timothy A. Fletcher [a,*], Tatiana Kim [a], Timothy J. Dodwell [b], Richard Butler [a], Robert Scheichl [c], Richard Newley [a]

[a] Department of Mechanical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom
[b] College of Mathematics, Engineering and Physical Sciences, University of Exeter, Exeter EX4 4PY, United Kingdom
[c] Department of Mathematical Sciences, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom

ARTICLE INFO

Article history:
Available online 2 March 2016

Keywords:
Curved laminates
4-Point bending
Free edge
Edge effect

ABSTRACT

Large aerospace parts are typically certified by testing narrow specimens, such as curved laminates, which have exposed free edges. These edges (not present in the production part) have been found to reduce the 3D strength of curved laminates by over 20%, showing this certification method is unreasonably conservative. The free edges also create a singularity, such that finite element (FE) modelling is challenging, which is typically approximated using non-linear analysis of cohesive interlaminar zones. A new treatment process is developed whereby a layer of resin is applied to the free edges of curved laminates. This significantly reduces the edge effect and delays failure. The resin edge treatment increases the strength of the curved laminate test specimens by 16%. The treatment also simplifies FE modelling by allowing for non-zero stresses normal to the laminate edge, removing the singularity. This enables use of linear FE models, which converge at the laminate edge. A linear FE method developed in this paper is conservative and predicts the strength of treated curved laminates to within 5% of the average test value. Hence it is shown that the resin edge treatment can be used to improve reliability of both certification tests and FE models.

1. Introduction

The certification of aircraft is typically validated with a programme of testing. Thousands of tests are carried out on small scale coupons, with fewer and fewer carried out as the test parts get larger and more complex. It is important that at every scale the test is representative of the final product. The response of curved laminates to out-of-plane loading can be assessed by conducting a 4-point bend test [1]. These tests are typically carried out on small curved laminate specimens, several orders of magnitude narrower than the final product. For UD CFRP material, considered in this paper, bending tests induce high interlaminar stresses at the free edges of such narrow specimens, generated by the mismatch in elastic properties between plies with different fibre orientations. This edge-effect generally causes narrow specimens to fail at a significantly lower load than would be predicted by 2D, plane strain analysis. It therefore results in the narrow specimen not being representative of the final product, where the final product is very wide and/or is built into surrounding structure at its ends, such that it has no free edges.

The high stress intensity caused by free edges has long been a known issue and there have been many techniques proposed to reduce it. Caps can be bonded onto the free edges and this has been shown to reduce interlaminar normal stress but does not significantly reduce interlaminar shear stress [2–5]. The edges can be altered to tailor structural properties, using an isotropic filler material and by changing the orientation of a ply near the free edge to reduce interlaminar stresses in this region [6]. A number of other techniques have been used to mitigate the free edge effect, such as stitching along the edges [7] and the use of adhesive layers [8]. It has also been shown that the stacking sequence of the laminate is important and can be tailored to influence the interlaminar stresses near a free edge [9]. The vast majority of edge protection techniques have been applied only to flat laminates under axial loading.

Evaluating the edge effect is challenging and many analytical and numerical approximation methods have been proposed. Literature surveys of these can be found in review articles [10,11] but

* Corresponding author.
E-mail addresses: t.a.fletcher@bath.ac.uk (T.A. Fletcher), t.kim@bath.ac.uk (T. Kim), t.dodwell@exeter.ac.uk (T.J. Dodwell), r.butler@bath.ac.uk (R. Butler), r.scheichl@bath.ac.uk (R. Scheichl), rn379@bath.ac.uk (R. Newley).

http://dx.doi.org/10.1016/j.compstruct.2016.02.074
0263-8223/

Nomenclature

Abbreviations

CBS	curved beam strength – required moment per unit width for failure
CFRP	carbon fibre reinforced plastic
FE	finite element
FEA	finite element analysis
ILSS	interlaminar shear strength
LHS	left hand side
UD	uni-directional
UTS	ultimate tensile strength

Symbols

D	roller diameter
d_x	horizontal distance between centre of adjacent upper and lower roller
d_y	vertical distance between centre of adjacent upper and lower roller
i, j	local directional parameters with 1 and 2 in-plane and 3 out-of-plane
P	applied load
Φ	angle between limbs of curved laminate and horizontal
s_{ii}, s_{ij}	material allowable
σ_{ii}	direct stress
t	thickness of curved laminate
τ_{ij}	shear stress
w	width of curved laminate

there are no analytical methods that calculate the exact stresses at the free edge. An approximate analytical method for calculation the interlaminar stresses for laminated plates is presented in [12]. This work shows the singular behaviour of interlaminar normal and shear stresses near laminate free edges, which gives rise to the challenges and complexity in modelling such problems. Linear FE analysis often results in highly localised, mesh dependent stresses near the edge that are higher than the strength of the material. A method for assessing when these high stresses will lead to failure has been developed using linear elastic fracture mechanics [13]. Non-linear FE analysis of cohesive zones is often performed in order to capture failure initiation and predict composite laminate strength, such as 3D non-linear modelling of delamination damage onset and growth in composite spar wingskin joints [14]. 3D non-linear FE modelling is generally very computationally expensive. An alternative method for assessing the free edge effect for composite flat plates is described in [15]. This consists of assessing 2D and 1D problems through a series of iterations, which produces quasi-3D results less costly than full 3D FEM computations.

In this paper a number of 4-point bend tests have been carried out alongside linear FE analysis to investigate the strength of curved laminates. In this way the edge effect is established as well as the convergence of the FE models. Thereafter a resin edge treatment designed to protect the free edges is developed and explored in order to reduce the edge effect. The treatment consists of a band of resin applied to the free edges of the laminate. A diagram of the curved laminates is shown in Fig. 1, illustrating the free edges and resin edge treatment. It has been shown that reducing the fibre volume fraction towards the free edge reduces interlaminar stresses for a flat laminate under axial extension [16]. The technique presented in this paper has some similarities to this, with effectively a fibre volume fraction of zero within the resin edge treatment zone. However, a key benefit of the new treatment is that it can be applied retrospectively to samples cut from larger parts.

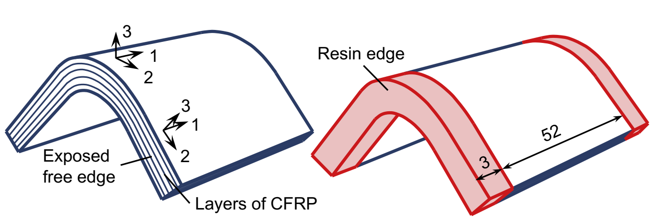

Fig. 1. Curved laminates without and with resin edge treatment, showing the free edge in the untreated sample and how this is protected by resin for the treated sample. The axes show the global coordinate system. Fibres in 0° plies are oriented along the 1-axis and 90° plies, along the 2-axis. Dimensions in mm, not to scale.

2. Test methodology

2.1. Rig design and CBS calculation

The curved beam strength (CBS) is used as a metric for quantitatively assessing and comparing the strength of the curved laminates. CBS is defined as the applied bending moment per unit width (or running moment) at failure. The CBS of curved laminate specimens was assessed by means of a 4-point bend test. The test setup was adapted from ASTM D6415 [1]. An unfolding moment was generated by 4 rollers attached to a test rig, as shown schematically in Fig. 2. Well-lubricated, smooth steel rollers were used in order to ensure they rotated freely within their housing and could not transfer load into the coupon via shear, which would invalidate many of the modelling assumptions. The displacement of the upper two rollers was controlled by an Instron machine at a rate of 1 mm/min. By monitoring the load and displacement, the applied moment, and hence CBS, was calculated from [1] according to

$$\mathrm{CBS} = \left(\frac{P}{2w\cos\Phi}\right)\left(\frac{d_x}{\cos\Phi} + (D+t)\tan\Phi\right) \quad (1)$$

$$\sin\Phi = \frac{-d_x(D+t) + d_y\sqrt{d_x^2 + d_y^2 - D^2 - 2Dt - t^2}}{d_x^2 + d_y^2}, \quad (2)$$

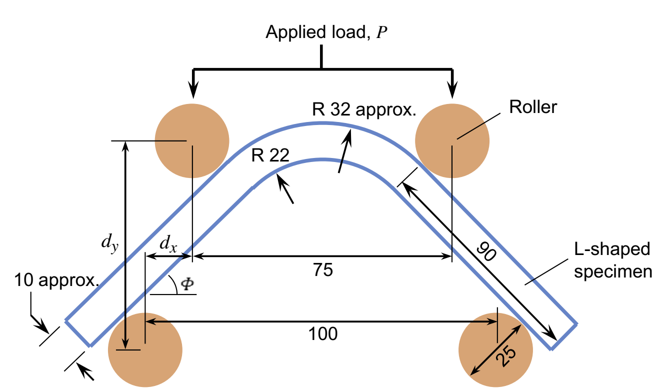

Fig. 2. Schematic of test setup in cross-section. All dimensions in mm.