Composite Structures 138 (2016) 122–133

Contents lists available at ScienceDirect

Composite Structures

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

Buckling and delamination growth behaviour of delaminated composite panels subject to four-point bending

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ARTICLE INFO

Article history:
Available online 7 December 2015

Keywords:
Buckling behaviour
Delamination growth
CFRP laminates
3D-DIC
FE analysis

ABSTRACT

Buckling behaviour and delamination growth have been investigated in Carbon Fibre-Reinforced Plastic (CFRP) laminates with artificial and impact-induced delaminations when subject to four-point bending. The energy of the impact was such that the induced damage, observed using ultrasound, did not extend across the entire width of the laminates and was barely visible on the impacted face. Stereoscopic digital image correlation was used to measure the evolution of the deformation of the laminate during bending to structural failure; and the resulting full-field displacement maps and observations of failure modes from Scanning Electron Microscopy (SEM) were used to conclude that appropriately shaped and located artificial delaminations could be employed to represent damage-induced delaminations. This enabled the development of a non-linear Finite Element Analysis (FEA) incorporating a fibre/matrix constitutive model, a modified fibre/matrix failure criterion and a delamination growth criterion to examine the interaction between the buckling behaviour and delamination growth. The predictions of the surface displacements in bending were validated, with the aid of image decomposition, using the measured data fields for a crossply laminate. The model reliably predicted the load–displacement curve and the propagation of damage in laminates with a low level impact damage, which did not extend across the width of laminates, unlike in prior reported models.

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1. Introduction

Carbon Fibre Reinforced Plastics (CFRP) have high specific stiffness and strengths that make them attractive in applications that demand light-weight and resilient structures. However, in their laminate form, which is used extensively in the aerospace industry, they suffer from damage propagation occurring from small delaminations that may occur during manufacturing or as a result of low energy impacts in service. When laminates with a local delamination are subject to bending it is usual for the delamination to grow via a number of mechanisms including matrix cracking, fibre breakage and fibre/matrix debonding. Local buckling of the laminate may occur in the vicinity of the delamination. Recently, the authors have used stereoscopic digital image correlation to examine the behaviour in bending of small delaminations introduced during manufacturing of cross-ply laminated composites [1]. They found that critical localised buckling load was typically about 60% of the ultimate bending moment and was a function of the initial size of the delamination. The development of damage from circular and elliptical initial delaminations was different with delamination growth occurring in the transverse direction for circular delaminations prior to buckling and being dominated by longitudinal damage propagation post-buckling whereas elliptical delaminations tended to always extend in the longitudinal direction regardless of their orientation. Whilst these experiments were useful in elucidating the mechanisms and development of damage, on their own they cannot provide insight into the likely performance of composite components. For this purpose appropriate theories are needed from which models and simulations can be constructed. There has been extensive prior work in this field [2] with the work by Chai et al. [3] perhaps being the first analytical description of local buckling in composite panels subject to compression and subsequently Kardomateas [4] developed an analytical model of sub-laminate buckling in delaminated composites in bending. More recently, Murphy and Nichols [5] used experimental data to develop and validate a two-dimensional analytical model of a delamination in composite beam in bending, which was also simulated using the finite element method by Kinawy et al. [6]. Riccio

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http://dx.doi.org/10.1016/j.compstruct.2015.11.054
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Nomenclature

C_d	damaged elasticity matrix of CFRP single layer
C^0	elasticity matrix of CFRP single layer
d	damage parameter for cohesive law
d_{fc}, d_{ft}, d_{mc}, d_{mt}	Hashin's damage variable associated with fibre compression, fibre tension, matrix tension and matrix compression respectively
D	elastic constant defined by Eq. (6)
E_1, E_2, E_3	elastic constants, defined in Eq. (4)
F_{fc}, F_{ft}, F_{mc}, F_{mt}	failure indexes associated with fibre compression, fibre tension, matrix tension and matrix compression respectively
G_2	mixed mode critical energy release rate
G_{12}, G_{13}, G_{23}	components of the elasticity matrix, Eq. (4)
G_{IC}, G_{IIC}, G_{IIIC}	critical strain energy release rates for mode I, II and III respectively
K	penalty stiffness
s_a, s_i	Tchebichef moments representing the results from specimen with artificial and impact damage respectively
s_{ex}, s_{fea}	Tchebichef moments representing the results from the experiment and finite element analysis respectively
S^L	failure stress in shear in 1–2 plane
S^T	failure stress in shear in 2–3 plane
u_{meas}, u_{deco}	uncertainty arising from measurement and image decomposition
X^C	compression strength in fibre direction
X^T	tensile strength in fibre direction
Y^C	compression strength in matrix direction
Y^T	tensile strength in matrix direction
α	parameter defined in Eq. (9)
β	parameter defined in Eq. (9)
δ_I, δ_{II}, δ_{III}	mode I, II and III displacements respectively
δ_m	total mixed-mode relative displacement defined by Eq. (13)
δ_m^0, δ_m^f	relative displacements corresponding to the onset of softening and total decohesion respectively and defined in Eqs. (14) and (15)
ε_{11}, ε_{22}	direct strains
ε_{12}, ε_{23}, ε_{13}	shear strains
$\boldsymbol{\varepsilon}$	strain tensor
η	empirical parameter defined in Eq. (11) and Table 3
σ	nominal, direct stress in the pure mode I
$\boldsymbol{\sigma}$	stress tensor
$\hat{\sigma}$	mode I ultimate strength
τ_1, τ_2	nominal shear stress along first and second shear directions
$\hat{\tau}$	ultimate shear strength
υ_{12}, υ_{13}, υ_{21}, υ_{23}, υ_{32}	elastic constants defined in Eq. (6)
ξ	parameter defined in Eq. (14)

and Pietropaoli [7] introduced circular delaminations into their non-linear finite element model of fibre–matrix damage evolution in a composite panel subject to pure compression. However, most prior studies have considered single through-the-width delaminations that extend across the whole cross-section of the laminate. This is perhaps because through-the-width delaminations are essentially one-dimensional in behaviour since they can only extend in the length direction and hence, are easier to model. Through-the-width delaminations are less likely to occur with barely visible impact damage (BVID) when small enclosed delaminations are likely to be more insidious and hence are of significant practical interest.

Therefore, in this paper we have investigated, using experiments and computational simulations, the interaction of buckling behaviour, delamination growth and matrix/fibre cracking in CRFP laminates subject to four-point bending that have post-impact delaminations which initially do not extend across the width, i.e. they might be termed enclosed delaminations. The aim of this study was to develop a high-fidelity model of the buckling behaviour and delamination growth in CFRP composites subject to bending loads after impact. Fracture analysis has been employed to support the development of a non-linear finite element analysis incorporating fibre/matrix failure and delamination growth criteria, which has been utilised to examine the interaction between the buckling behaviour and delamination growth. Experiments have been used to establish that CFRP composite laminates with an appropriate artificial delamination of the type employed in our previous work exhibit an equivalent response prior to ultimate failure, to laminates with delamination damage due to an impact. This permits the simplification of the computational model. In the final phase of the reported work, data fields for displacements and strains have been acquired using stereoscopic digital image correlation and used to validate the computational model by comparing the predictions with measurements using an image decomposition method for an eleven-ply crossply CFRP laminate. Once fully validated, the computational model could provide a reliable means to predict the effect of delamination size and shape on the buckling and post-buckling behaviour of composite laminates in loading conditions that it is difficult or expensive to conduct experimentally.

2. Experimental investigation

2.1. Specimen manufacture

In the first phase of the study a series of low velocity impact tests were performed to establish the typical shape and extent of barely visible impact damage (BVID) so that a suitable artificial delamination could be designed to be representative of BVID. This representative delamination was then used in the simulation phase of the study. Laminate specimens were manufactured following the identical procedure to that used previously by the authors [1]. Laminates with a stacking sequence of [0/90/0/90/0/90/0/90/0/90/0] and nominally 80 mm wide, 260 mm long and 3 mm thick were manufactured from Carbon Fibre Reinforced Plastic (CFRP) prepreg layers (HexPly M10 RUD150 from Hexcel Corporation, USA[2]), which consisted of uni-directional high-strength carbon fibres of mass 150 g/m^2 with a nominal fibre volume fraction of 52% in a 120 °C curing epoxy resin content of 38% by weight. The stacking sequence was chosen for its symmetry, ease of reproducibility in the experiments and its reduced computational modelling requirement compared to multi-directional lay-ups. The specimens were cured in a hot press (Meyer, USA) at 1.5 bar and 150 °C for 20 min after heating at 3 °C per minute and was subsequently cooled naturally to room temperature under pressure, which resulted in a laminate of nominal thickness 3.0 mm.

In addition to manufacturing a series of virgin specimens, a specimen was produced with an artificial delamination by introducing a 0.08 mm thick film of PTFE between an outer laminate and the immediate sub-surface laminate to prevent adhesion

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[2] Datasheet available at www.hexcel.com/Resources/DataSheets/Prepreg-Data-Sheets/M10R_eu.pdf.

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