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Fracture behaviour of triaxial braided composites and its simulation using a multi-material shell modelling approach

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ABSTRACT

The translaminar fracture response of triaxial braided composites was analysed by means of Compact Tension tests. Different values of critical strain energy release rate for fracture along the main material directions were estimated by applying two different data reduction methods to the experimental results. The fracture mechanisms were analysed to provide physical justification for such anisotropic behaviour. Possible laminate thickness effects were studied but judged to have negligible impact in the fracture toughness of these materials. A numerical methodology based on a Multi Material Shell approximation is proposed to simulate fracture of triaxial braided composites. The modelling approach is based on the discretization of the braiding architecture at the Gauss point level of standard shell elements including the corresponding yarn geometrical parameters. At constitutive level, Continuum Damage Models were used to simulate independently the brittle orthotropic yarns and the elasto-plastic isotropic resin matrix. This approach was validated by correlation between simulations of the Compact Tension tests and the corresponding experimental results. In spite of the modelling simplifications, the remarkable results achieved reveal an efficient virtual testing approach that can be used for the analysis fracture of triaxial braided materials at structural level.

1. Introduction

Textile composites are being used in a large range of applications, from aeronautical to automotive and energy sectors, because of the favourable combination of specific mechanical properties and cost. Among them, triaxial braided composites are proven to offer high in-plane shear stiffness, strength and drapability, due to the addition of the axial yarns in the textile architecture during the manufacturing of the preform [1]. There is also indication that their impact response is superior to traditional woven composites, what can be to a large extent attributed to the enhanced fracture behaviour of these materials [2,3]. However, there is little information available about fracture of triaxial braided composites, not to mention appropriate models to predict their mechanical response up to failure.

Fracture of fibre reinforced composites having three-dimensional fibre architectures, geometric discontinuities or inherent material defects is a complex process due to the involvement of several failure mechanisms in the breakage of

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Nomenclature

CC	Compliance Calibration method
CDM	Continuum Damage Model
CLT	Classical Laminate Theory
CMOD	Crack Mouth Opening Displacement
CT	Compact Tension
DIC	Digital Image Correlation
LEFM	Linear Elastic Fracture Mechanics
MMS	Multi-Material Shell
α, β, χ	compliance curve fitting parameters
α_{sh}	shear-stress coupling factor in longitudinal yarn failure
$\hat{\sigma}_1, \hat{\sigma}_2, \hat{\tau}_{12}$	effective plane-stress tensorcomponents
μ	friction coefficient
ν_m	pure matrix Poisson's ratio
ν_{12}, ν_{13}, ν_{23}	yarn Poisson's ratios
σ_{ft}	fibre tensile strength
σ_{mt}, σ_{mc}	pure matrix tension/compression strength values
a, a_0, Δ_a	crack length, initial crack length, total crack growth
C	specimen compliance
d_f, d_m, d_s	yarn damage variables
E_1, E_2, G_{12}	yarn orthotropic elastic constants
E_c	total fracture energy dissipation
E_m	pure matrix elastic modulus
E_x, E_y, G_{xy}	laminate in-plane elastic moduli
F_{ft}, F_{fc}, F_{mt}, F_{mc}	yarn failure indices
F_{v_f}	yarn local fibre volume fraction
G_{Ic}^L, G_{Ic}^T	laminate fracture energies for longitudinal and transverse loading directions
G_m	pure matrix fracture energy
G_{ft}, G_{fc}, G_{mt}, G_{mc}	yarn fracture energies
G_{Ic}	critical strain energy release rate
G_{v_f}	geometrical volume fraction
K_{Ic}	critical stress intensity factor
L_c	characteristic element length
l_{fpz}	length of the fracture process zone
P_c	critical load to cause fracture
t, w	specimen thickness and length
X_T, X_C, Y_T, Y_C, S_L, S_T	yarn unidirectional strength values
ν_{xy}	laminate in-plane Poisson's ratio

the material. Such is the case of triaxial braided composites wherein the damage mechanisms are numerous and control the fracture behaviour of the material. A few experimental ways have been proposed to characterize the intralaminar and translaminar fracture behaviours of composites, from which the most commonly adopted is the Compact Tension (CT) test procedure [4] adapted from the corresponding test standard (ASTM E399) recommended for metals [5]. Due to its practicality in the extraction of fracture resistance curves (*R*-curves), this test procedure has been extensively applied to the characterization of unidirectional laminates along with several possible data reduction methods [6–9], but less used with textile composites. To refer to a few examples, the translaminar fracture toughness of warp-knitted carbon fibre composites was studied in [10,11], the application of Digital Image Correlation (DIC) techniques to study the damage mechanisms associated with Woven E-glass/epoxy composites was explored in [12], and test methods for fracture characterization of woven composites were proposed and analysed by Blanco et al. [13,14].

Triaxial braided composites are a subset of textile composites in which two bias yarns alternate over and under axial yarns. This complex fibre architecture is said to produce mechanical interlocking and extra resistance to crack initiation and propagation. As such, these braided composites were reported to be materials with enhanced fracture toughness [1,15]. However, fracture characterization of triaxial braided composites is complicated due to the material inhomogeneity at the unit cell level. Therefore there is a lack of experimental data to evaluate the potential improvements offered by these architectures in terms of strain energy dissipation.

In the work presented in this paper, the CT-based test methodology was employed to characterize the translaminar fracture behaviour of triaxial braided composites. Given the nature of these composite architectures, the translaminar fracture toughness represents a homogenisation of the energy dissipated due to various failure mechanisms within the yarns (fibre