Composites Science and Technology 135 (2016) 67–75

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Experimental and numerical investigation of intra-laminar energy dissipation and size effect in two-dimensional textile composites

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ARTICLE INFO

Article history:
Received 19 May 2016
Received in revised form
17 July 2016
Accepted 24 August 2016
Available online 4 September 2016

Keywords:
Textile composites
Non-linear fracture mechanics
Damage mechanics
Size effect
Two-dimensional composites
Microplane model

ABSTRACT

Design of large composite structures requires understanding the scaling of their mechanical properties, an aspect often overlooked in the literature on composites.

This contribution analyzes, experimentally and numerically, the intra-laminar size effect of textile composite structures. Test results of geometrically similar Single Edge Notched specimens made of $[0^\circ]_8$ epoxy/carbon twill 2 × 2 laminates are reported. Results show that the nominal strength decreases with increasing specimen size and that the experimental data can be fitted well by Bažant's size effect law, allowing an accurate identification of the intra-laminar fracture energy of the material, G_f.

The importance of an accurate estimation of G_f in situations where intra-laminar fracturing is the main energy dissipation mechanism is clarified by studying numerically its effect on crashworthiness of composite tubes.

Simulations demonstrate that, for the analyzed geometry, a decrease of the fracture energy to 50% of the measured value corresponds to an almost 42% decrease in plateau crushing load. Further, assuming a vertical stress drop after the peak, a typical assumption of strength-based constitutive laws implemented in most commercial Finite Element codes, results in an strength underestimation of the order of 70%.

The main conclusion of this study is that measuring accurately fracture energy and modeling correctly the fracturing behavior of textile composites, including their *quasi-brittleness*, is key. This can be accomplished neither by strength- or strain-based approaches, which neglect size effect, nor by LEFM which does not account for the finiteness of the Fracture Process Zone.

1. Introduction

Thanks to their outstanding specific mechanical properties, the engineering use of textile composites is becoming broader and broader. Current applications include land, marine and air transportation, wind and tidal energy production, and blast protection of civil infrastructures and vehicles [1–3]. However, design of large composite structures requires capturing the scaling of their mechanical properties, an aspect often overlooked in the literature on composites. This can be achieved only by abandoning the current design paradigm, which relies on strength-based approaches incapable of predicting any scaling, and acknowledging the *quasi-brittle* character of these materials.

Due to the complex mesostructure characterizing textile composites (and other quasibrittle materials such as concrete, nanocomposites, ceramics, rocks, sea ice, and many bio-materials, just to mention a few), the size of the non-linear Fracture Process Zone (FPZ) occurring in the presence of a large stress-free crack is usually not negligible [4–6]. The stress field along the FPZ is nonuniform and decreases with crack opening, due to discontinuous cracking, crack bridging by fibers, and frictional pullout of inhomogeneities. As a consequence, the fracturing behavior and, most importantly, the energetic size effect associated with the given structural geometry, cannot be described by means of the classical Linear Elastic Fracture Mechanics (LEFM). To capture the effects of a finite, non-negligible FPZ, the introduction of a characteristic (finite) length scale related to the fracture energy and the strength of the material is necessary [4,7]. However, estimating accurately these material properties is far from easy

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http://dx.doi.org/10.1016/j.compscitech.2016.08.021
0266-3538/

because the fracture tests usually exhibit an extreme snap-back at peak load, with a loss of stability [7,8].

A possible way to overcome these issues is size effect testing [4,7]. This study proposes an experimental and numerical investigation on the efficacy of the intra-laminar size effect testing to characterize the fracturing behavior of textile composites. It is worth remarking here that the size effect method of measuring the fracture properties is easier to implement than other methods because only peak load measurements are necessary. The post-peak behavior, crack tip displacement measurement, and optical measurement of the crack tip location are not needed, and even a soft testing machine without servo-control can be used.

2. Test description

2.1. Materials

Experiments were conducted on specimens manufactured by compression molding. A Bisphenol A diglycidyl ether (DGEBA)-based epoxy resin was chosen as polymer matrix whereas the reinforcement was provided by a twill 2 × 2 fabric made of carbon fibers. The material was characterized following the ASTM standard procedures [12] testing $[0^\circ]_8$ and $[45^\circ]_8$ coupons under uniaxial tension. The results of this characterization are listed in Table 1.

2.2. Specimen characteristics

Following Bažant et al. [4,7], intra-laminar size effect tests were conducted on single-edge-notched tension (SENT) specimens (see Fig. 1), using a $[0^\circ]_8$ lay-up with a constant thickness of approximately 1.9 mm. The SENT specimens were preferred to Double-Edge Notched Tension (DENT) specimens, for which two cracks typically initiate at the notch tips but ultimately only one of the two cracks can propagate, causing the response to be asymmetric [13].

Specimens of three sizes (three for each size), geometrically scaled in two-dimension (see Table 2) as 1:2:4, were tested. The first half of the notch was made by means of a diamond coated bend saw which provided a width of roughly 1 mm whereas the second half was made using a diamond-coated miniature blade thanks to which a width of 0.2 mm was obtained in all cases (Fig. 2). Accordingly, the resulting crack tip radius was 0.1 mm, about 70 times smaller than the size of a Representative Unit Cell (RUC) of the material. It is worth noting that the sawing action of the blade prevented the formation of a Fracture Process Zone (FPZ) before running the tests contrarily to common pre-fracturing procedures [14].

All the specimens were prepared with 38 mm long glass/epoxy tabs for gripping purposes. The tab length (grip constraint) was not scaled because it has no appreciable effect on the stored energy and because fracture always occurs away from the grips.

The top surface of all the SENT specimens was treated to allow Digital Image Correlation (DIC) analysis. A thin layer of white paint was deposited on a $D \times D$ area embedding the crack. Then, black speckles of average size 0.01 mm were spray-painted on the surface after drying.

Table 1
Properties of carbon twill 2 × 2/epoxy composite.

Description	Symbol (units)	Measured value
Fiber volume fraction	$V_f\,(-)$	0.54
Laminate thickness	t (mm)	1.9
In-plane modulus	$E = E_1 = E_2$ (GPa)	53.5
In-plane shear modulus	$G = G_{12}$ (GPa)	4.5
In-plane Poisson ratio	$\nu = \nu_{12} = \nu_{32}\,(-)$	0.055
In-plane tensile strength in direction 1 and 2	$F_{1t} = F_{2t}$ (MPa)	598

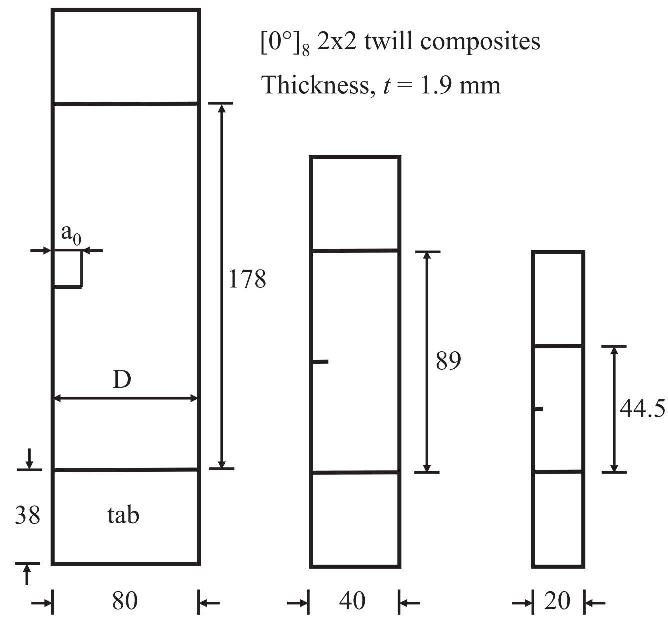

Fig. 1. Geometry of Single Edge Notch Tension (SENT) specimens under study. Units: mm.

Table 2
Geometrical specifications of the SENT specimens under study.

Size	Width, D	Gauge length, L	Length, $L = L{+}2L_t$	Crack length, a_0	Thickness, t
Small	20	44.5	120.5	4	1.9
Medium	40	89.0	165.0	8	1.9
Large	80	178.0	254.0	16	1.9

Units: mm. Tab length $L_t = 38$ mm for all investigated sizes.

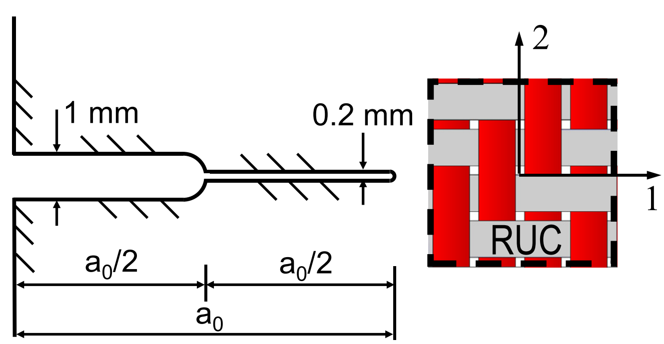

Fig. 2. Geometry of the notch (scaled for each size) and schematic of the Representative Unit Cell of the twill 2 × 2 composites under study.

2.3. Testing

The tests were performed on a closed-loop servohydraulic MTS machine with 89 kN capacity and at constant crosshead rate (stroke control). The rate was adjusted for the different sizes to achieve roughly the same strain rate of 0.2%/min in the gage section. With such settings, the test lasted no longer than approximately 10 min for all specimens.

Stroke, force, and loading time were recorded with a sampling frequency of 10 Hz. A DIC system from Correlated Solutions [15]