Composites: Part A 87 (2016) 66–77

Contents lists available at ScienceDirect

Composites: Part A

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

Damage sequence in thin-ply composite laminates under out-of-plane loading

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ARTICLE INFO

Article history:
Received 10 November 2015
Received in revised form 8 March 2016
Accepted 8 April 2016
Available online 13 April 2016

Keywords:
A. Polymer-matrix composites (PMCs)
B. Impact behavior
C. Damage mechanics
D. Fractography

ABSTRACT

The study of the damage sequence in polymer-based composite laminates during an impact event is a difficult issue. The problem can be more complex when the plies are thin. In this paper, quasi-static indentation tests were conducted on thin-ply laminates to understand qualitatively the damage mechanisms and their sequence during low-velocity impact loading. TeXtreme® plain weave plies were used with two different thicknesses, 0.08 mm and 0.16 mm (referenced as ultra-thin-ply and thin-ply, respectively), and tested under different load levels. Load–displacement curves were analyzed and the extent of damage was inspected using optical microscopy and ultrasonic technique. The results showed that the damage onset occurs earlier in thin-ply laminates. The damage onset in thin-ply laminates is matrix cracking which induces delaminations, whereas for ultra-thin-ply laminates is due to delaminations which are induced by shear forces and small amount of matrix cracking. Moreover, the fiber breakage appears earlier in ultra-thin-ply laminates.

1. Introduction

Polymer-based laminated composite materials are used extensively in structural applications, not only as secondary structures, but also as primary structures [1]. However, composite laminates are vulnerable to damage accumulation (i.e. matrix cracking, delamination, and fiber breakage), which often is difficult to detect by simple visual inspection and can severely reduce the mechanical properties of the structure, such as the compressive strength after out-of-plane impact loading [2–11].

With the aim of delaying the onset and propagation of damage, reducing the ply thickness has been reported to have benefits in lessening intra-laminar [12–16], inter-laminar [17,18] and splitting damage [19,20], without using special resins and/or fiber architectures [21–24]. The use of thin- or ultra-thin-ply laminates, with thicknesses below 0.1 mm, has been analyzed in the recent years by several authors [15,25]. In addition, the strength performance in other well-known tests on composite material coupons is enhanced when using thin-ply technology. Some examples from the literature are: Unnotched Tension [21,23,26], Bearing [26], Open-Hole Compression [21,23,26], and Compression After Impact [10,21,27]. The results of these tests for thin- and thick-ply laminates are summarized and compared in Table 1; as can be observed, significant strength improvement is obtained for thin-ply laminates.

For the particular case of damage resistance assessment in low-velocity impact loading, Yokozeki et al. [23,28] reported that the overall extent of delamination is independent of the ply thickness. However, the projected delamination areas reported by González et al. [10] showed a clear effect of the ply thickness on the damage resistance: the thicker the ply thickness is, the larger the delamination area is. Saito et al. [27] and Amacher et al. [26] reported that the ply thickness has a great effect on the delamination area: the thicker the ply thickness is, the smaller the delamination area is. In any case, the understanding of the appearance and growth of the different damage mechanisms present in an impact event, as well as their interactions, has not been sufficiently consolidated. More studies should be carried out in order to improve the damage resistance and the damage tolerance of composite structures that are susceptible to impact.

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http://dx.doi.org/10.1016/j.compositesa.2016.04.010
1359-835X/

Table 1
Strength performance on quasi-isotropic laminates: Unnotched Tension (UT), Bearing (B), Open-Hole Compression (OHC), and Compression After Impact (CAI).

Ref.	Material	Fabric	Ply thickness [mm]		UT [MPa]		B [MPa]		OHC [MPa]		CAI [MPa]	
			t_{thick}	t_{thin}	Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin
[21]	T800S/BT250E-1	Unidirectional	0.125	0.040	700	980	–	–	547	490	–	–
[23]	MR50K/#1063EX	Unidirectional	0.160	0.080	812	974	–	–	296	323	228	246
[10]	AS4/8552	Unidirectional	0.728	0.182	–	–	–	–	–	–	105	133
[27]	TR50S/#350	Unidirectional	0.150	0.038	–	–	–	–	–	–	380	450
[26]	M40JB/80EP(CF)	Unidirectional	0.300	0.030	595	847	476	584	215	255	–	–

Low-velocity impacts caused by large-mass impactors yield a type of response which can be approximated as quasi-static, where the deformation mode approaches a purely static deformation, and the load and the deflection are in phase [29]. In this sense, the impact event can be analyzed as a static indentation problem. Indeed, experimental results correlate well with this assumption for low- and medium-impact energies [30–32]. Therefore, Quasi-Static Indentation (QSI) tests can provide a meaningful indication on the damage mechanisms occurring during low-velocity impacts [33–35].

The permanent indentation depth is an interesting parameter in damage assessment procedures for the aeronautical industry. It is used as an indication of the severity of the internal damage induced by impact, e.g. size of delaminations. If the indentation depth is below the threshold of visual detectability, known as Barely Visible Impact Damage threshold (BVID), the structure is supposed to withstand the ultimate design load [36]. However, in some cases, the structure can be considerably damaged despite the indentation being less than the BVID threshold (matrix cracking, delaminations and even fiber breakage), and therefore, the structure cannot withstand the design load. In consequence, composite structures in which the indentation depth can give a reliable indication about the severity of the damage induced inside the structure is of clear interest.

The present paper analyzes the associated damage mechanisms and their sequence in thin- and ultra-thin TeXtreme® plain weave ply composite laminates under QSI tests. Inspections by Optical Microscopy and ultrasonic C-scan technique were performed to identify the different damage mechanisms that occur at different indenter displacements. Also, indentation profiles of the indented surfaces were measured after the tests by means of a 3D coordinate measuring machine. Moreover, the relaxation of the damaged material was measured by means of a dent-depth gauge. Finally, the work concludes with a summary of the main findings of the study.

2. Materials and methods

The fiber material used in this study was Tenax®-E HTS45 12K 800tex of 240 GPa tensile modulus, presented as TeXtreme® plain weave with 20 mm wide yarn fabrics, manufactured by Oxeon AB. TeXtreme® plies are dry cross-ply non-crimp fabrics, where the excess of resin pockets is minimized. Thus the weight and strength are improved in comparison with conventional woven plies. It can be considered that the behavior of this type of plies is a combination of that of woven and unidirectional type plies since the yarns are wide. Two different ply thicknesses were considered: 0.08 mm and 0.16 mm (with 80 gsm and 160 gsm areal weights, respectively), which correspond to a yarn thickness of 0.04 mm and 0.08 mm, respectively. In the following, these plies are respectively identified as Ultra-Thin-Ply (UTP) and Thin-Ply (TP). The fibers were impregnated by HexFlow® RTM 6 mono-component epoxy system, supplied by Hexcel® by means of Resin Transfer Moulding (RTM) process. The curing temperature was 180 °C during 90 min. The glass transition T_g temperature of the RTM6 resin is 195 °C. The plies were coated with a binder, Bisphenol A with high molecular weight, to improve the interface properties in the laminate and to avoid the movement of the fibers during the manufacturing process. The manufactured laminated plates with UTP and TP both resulted in a fiber volume fraction of 57%, using EN 2564:1998 [37].

The stacking sequence of the manufactured plates was $[((45/-45)/(0/90))_n]_s$, with n equal to 7 and 14 for TP and UTP laminates, respectively; for both cases, the nominal laminate thickness was of 4.5 mm. The ASTM D7136 [38] test method for drop-weight impact event was taken as reference in order to define the specimen dimensions and the QSI clamping system. Therefore, the in-plane specimen dimensions were 150 mm × 100 mm, where the orientation 0° was aligned with the major in-plane dimension, i.e. 150 mm. The clamping system consists of a flat base with a 125 mm × 75 mm rectangular cut-out and four clamps with rubber tips which fix the specimen during the QSI tests. The indenter was hemispherical-shaped with a diameter of 16 mm and made of stainless steel. Fig. 1 illustrates the QSI test set-up with the clamping system, the specimen location, and the indenter. As can be observed, a laser displacement transducer MEL M70LL was used to measure the back-face displacement of the plate just in the indentation point. A white tape was glued on the back-face of the specimen to reduce the voltage noise and so improve the

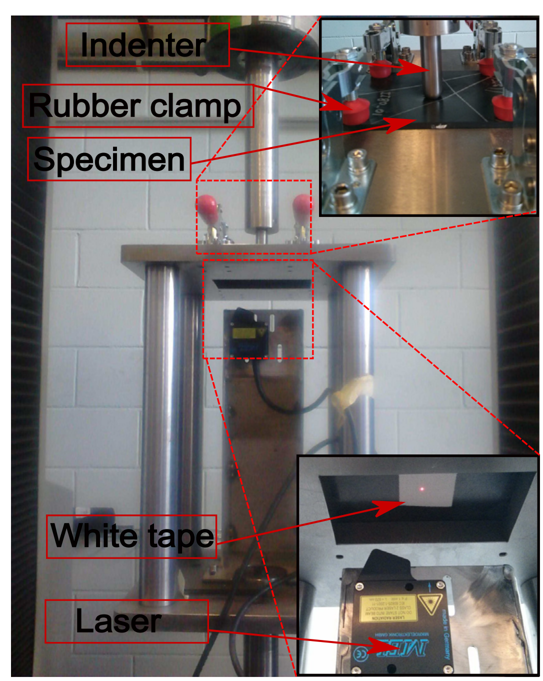

Fig. 1. Experimental test set-up of the QSI test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)