Composite Structures 163 (2017) 399–409

Contents lists available at ScienceDirect

Composite Structures

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

Acoustic emission and damage mode correlation in textile reinforced PPS composites

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ARTICLE INFO

Article history:
Received 24 October 2016
Revised 28 November 2016
Accepted 5 December 2016
Available online 18 December 2016

Keywords:
Thermoplastic
Textile composites
Acoustic emission
Cluster analysis
Damage

ABSTRACT

The paper applies the cluster analysis methodology to thermoplastic Polyphenylene sulphide (PPS) carbon woven composites. The experimental quasi-static tensile tests were assisted by: a digital camera for digital image correlation (DIC) evaluation of the full field strain; a digital camera for local damage observation; acoustic emission (AE) sensors for measurement of the acoustic emission features during loading. The experimental data and the subsequent cluster analyses of the AE events show a similar distribution of the AE clusters for the considered thermoplastic carbon composites and other thermoset woven composites described in the literature. The boundaries of those clusters are different for some extent, while a typical damage mechanism, namely transverse cracks inside the yarns, was clearly correlated to the first cluster with lower amplitude and lower frequency acoustic events.

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1. Introduction

Acoustic emission (AE) registration with subsequent analysis of the AE event parameters is a recognised and widely used method for damage monitoring during loading of fibre reinforced composites, which provides information of damage processes in the specimen without stopping the test, at a good time resolution, also identifying the spatial origin of the events. Quasi-static tension test is probably the most common type of loading for which AE registration is routinely used.

AE is useful for identification of damage thresholds: load (or strain) levels which manifest different stages of damage development (Fig. 1). The first damage in textile composites typically appears in the form of transverse (to the loading direction) cracks inside the yarns or on the yarn boundaries (short designation: *t*). Cracks are developed by coalescence of initial micro-debondings on the fibre-matrix interface. Upon further load increase, the transverse cracks propagate along the yarn length. They also increase in numbers until a certain critical number is reached (saturation). Transverse cracks in resin rich pockets (*tm*) are usually cracks that originated inside yarns but then propagated into these areas. When the transverse cracks are well developed, they cause appearance of the local delaminations (*l*), triggered by shear stresses resulting from interaction of the transverse cracks with the longitudinal reinforcement. The longitudinal yarns are subject to Poisson contraction under tension; this deformation is constraint by the presence of the transverse yarns, which leads to development of tensile transverse stresses in the longitudinal yarns. When the transverse strength of the longitudinal yarns is exceeded by these stresses, they can start splitting (*sp*). The local delaminations progress, leading to larger inter-ply delaminations (*L*). The onset and propagation of delaminations between plies is dependent on the interlaminar fracture toughness of the composite. In the final stage, massive breakage of fibres in longitudinal yarns begins (*f*). The strain at which this happens in textile composites is typically below the ultimate strain of fibres. This reduction is caused by the fibre crimp and developed delaminations, which prohibit efficient stress transfer inside fibre bundles.

Fig. 1 presents this sequence of damage events. It suggests presence of two thresholds of the applied load. The first, designated as ε_1, corresponds to the onset of the transverse cracking (*t*-cracks), which may not at this stage span the whole width of the specimen, being limited by the yarn crimp and/or presence of stitching in the textile reinforcement structure. The second, designated as ε_2, corresponds to, on one hand, the onset of local delaminations (*l*-cracks) and, on the other hand, to the formation of "strong" transverse cracks, which span the width of the specimen.

The damage thresholds can be identified using acoustic emission (AE) registration during the tensile loading. In [1–3], it was proposed to use a curve of cumulative energy (*E*) of the AE events for identification of the damage thresholds. The reader is referred

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http://dx.doi.org/10.1016/j.compstruct.2016.12.012
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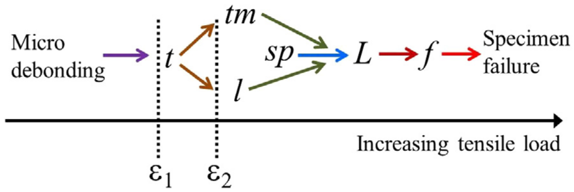

Fig. 1. A typical sequence of damage development in textile composites under tension loading.

also to [3] for details of the procedure of the damage thresholds identification using logarithmic and linear scales for the *E*(ε) curve, as adopted for the material studied in the present paper (see Section 4.2). This methodology was also applied in [4] for damage investigation in 5H satin carbon/PPS composites.

In the last five years, studies for the identification of the damage modes in fibre reinforced composites using cluster analysis added frequency and other descriptors of the AE events (e.g. [5–8]). The role of the frequency descriptors is not, however, generally accepted. For example, in [9] the cluster analysis has led to a conclusion that for flax reinforced thermoplastic composites the amplitude is the discriminating parameter for damage modes; frequency is not included in the set of descriptors. In [10], similar conclusion is drawn for the case of glass/epoxy composites in an open hole tensile test.

In [11–13], some of the present authors applied the approach of the damage mode identification based on the cluster analysis of AE events parameters to textile composites with thermoset matrices, which allowed physically based identification of the damage thresholds. These papers advance the methodology of the damage type identification, previously adopted by the authors (see e.g. [1–3,14]), which was based only on the acoustic energy thresholds, to the unsupervised cluster analysis, accounting also for the signal frequency. The pair of AE parameters (amplitude + a frequency parameter) was found to be the most important to discriminate the damage modes in tension loading of glass/epoxy and carbon/epoxy 2D and 3D woven composites. The cluster analysis of the AE events (presented briefly in Section 3) identifies typically three clusters of the events in the multi-parametric event space. The most important of the event parameters are the AE signal amplitude (expressed in dB and strongly correlated with the logarithm of the AE event energy) and one or another frequency-related parameters (peak frequency or frequency centroid). As shown in [11–13], in carbon/epoxy woven laminates the three clusters contain events originated from transverse matrix cracks (events with low frequency and low amplitude), local delaminations (low frequency and high amplitude) and fibre breakage (high frequency). The load values, corresponding to the onset of the AE events in the first and the second cluster correspond to the damage threshold values ε_1 and ε_2, respectively.

The present paper for the first time, in the Authors' knowledge, applies the cluster analysis methodology to thermoplastic (PPS) carbon woven composites. The research questions of the paper are: (1) is clustering of AE events in carbon woven composites with a brittle thermoplastic matrix the same as in similar composites with thermosetting matrix? (2) is there a difference in the cluster boundaries between these two types of composites? (3) can AE events in different clusters be identified with different damage modes?

The experimental investigation and the subsequent cluster analyses show a similar distribution of the AE cluster for the considered thermoplastic carbon composites and other thermoset woven composites described in the literature. The boundaries of those clusters are different for some extent, while a typical damage mechanism, namely transverse cracks inside the yarns, was clearly correlated to the first cluster with lower amplitude and lower frequency acoustic events.

2. Composite material and experimental procedure

Composite panels (41 × 41 cm) were fabricated using Polyphenylene sulphide (PPS) matrix (Ticona Fortron® 0205 [15]) and a five-harness satin weave carbon textile as reinforcement, whose main features are in Table 1a. The composite ([(0, 90)]$_3$) is similar to that adopted for the investigation detailed in [16], with the difference in fibre volume fraction, which is higher in the material studied in the present paper.

Measurements of the thickness and fibre volume fraction of the panels are listed in Table 1b.

Specimens for tensile test were extracted having the dimensions, according to standard ASTM D3039: total length 260 mm, gage length 160 mm, width 25 mm.

Tensile tests were performed using an Instron 4505 with a crosshead speed of 1 mm/min applying the load in the warp direction (considering the reinforcement balanced).

The experimental tests were divided in three sets.

Specimens of the first set were loaded up to failure to measure the main mechanical properties (elastic modulus and strength).

Specimens of the second and third set were equipped with two AE sensors (Digital Wave B-1025), 15 mm from each tab, to record the acoustic emission up to the 70% of the average ultimate tensile strength (from the first set of tests). This load level was set to avoid damage of the acoustic equipment. Details of the software and sensors for the AE recording are in Table 2. The parameters of the AE signals (energy, amplitude, frequency, etc.) were calculated using the standard functionalities of the adopted software (see Table 2).

For the second set of tests, AE were recorded in the complete zone between the two sensors (distance of 130 mm, see Fig. 2), while for the third set of specimens AE localized in the centre for a length of 5 mm were distinguished. This was used for the correlation of the acoustic emissions and the damage mode. In the same central zone, crack development was observed taking images (frequency 2 Hz) of the thickness of the specimens by the first CCD camera (size 1392 × 1040, 1.45 MP) (Fig. 2).

Before tests with AE recording, pencil tests were carried out on each specimen. Three 0.7 mm 2H pencil leads were broken in the centre of the specimen while registering AE. This allowed to check the accuracy of the AE location registered by the sensors and the actual location of events.

During loading of all specimens, images were acquired (frequency 2 Hz) using a LIMESS system, consisting of the second CCD camera (same features of the first one) (Fig. 2), and software for calibration and recording. The images post-processing allowed the measurement of the full field strain on the external surface of the specimen by the digital image correlation technique (DIC)

Table 1
Main characteristics (a) of the fabric reinforcement and (b) of the composite panels.

(a)	
Carbon Fibres	Torayca T300 J
Yarns	3 K
Yarn linear density [tex]	198
Fabric density [g/m^2]	285
Ends count [yarns/cm]	7
Pick count [yarns/cm]	7
(b)	
Number of plies	6
Fibre volume fraction [%]	57.6 ± 1.8
Thickness [mm]	1.65 ± 0.09

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