Statistical analysis of acoustic emission signals and tensile deformation measurement for three dimensional carbon fiber braided composites

Wei Zhou^{1,2} · Ya-jing Shang^{1,2} · Peng-fei Zhang^{1,2} · Han-fei Yin^{1,2} · Lian-hua Ma^{1,2}

Received: 7 April 2020 / Accepted: 12 June 2020 / Published online: 17 June 2020
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Abstract

Accurate assessment for mechanical and damage behaviors of three dimensional carbon fiber braided composites by acoustic emission technique is difficult in practical application. In this study, a statistical analysis approach with calculated amplitude spectrum, probability distribution and entropy is proposed to process acoustic emission signals. Moreover, the tensile behaviors and damage characteristics of three dimensional four directional and five directional braided composites are investigated systematically by combining digital image correlation and acoustic emission methods. The results indicate that three dimensional five directional braided composites possess excellent load-bearing and deformation resistibility capacity, owing to more compact preform structure with additional axial yarns. The acoustic emission statistical analysis method can be used as criteria to distinguish and quantify various irreversible damage and failure mechanisms in three dimensional braided composites. Furthermore, the deformation, damage and failure criterion for two types of composites are fully described based on deformation fields and acoustic emission signals.

Keywords Three dimensional braided composites · Deformation measurement · Statistical analysis · Acoustic emission · Digital image correlation

1 Introduction

Three dimensional (3D) braided composites are advanced composites, which have been increasingly studied and used in numerous fields such as aeronautics, vehicles and energy industries due to a series of excellent mechanical properties like favorable damage tolerance, outstanding fatigue resistance, high load-bearing capacity and low delaminating tendency than the traditional laminate composites [1–3]. Therefore, it is essential to reveal the mechanical behaviors and damage characteristics of 3D braided composites with complicated structures [4, 5].

In order to make better utilization of 3D braided composites, the deformation and damage properties under

different loading conditions have been studied by numerous researchers. Yan et al. [6] conducted the impact tests on 3D carbon/epoxy braided composites with various braiding angles and it was found that the specimens with larger braiding angles can sustain higher loads and own smaller impact damage zones. Zhai et al. [7] carried out bending mechanical tests on 3D braided composites, and the results demonstrated that bending strength of the specimens decreased with the increase of temperature increment. Furthermore, Li et al. [8] analyzed the damage and failure process of 3D braided T-joints composites under tensile tests. It was found that the damage mainly occurs in glue film zones and the interface of T-joints.

✉ Wei Zhou, zhouwei@126.com; zhouwei@hbu.edu.cn; ✉ Lian-hua Ma, lhma@hbu.edu.cn | ¹School of Quality and Technical Supervision, Hebei University, Baoding 071002, China. ²National and Local Joint Engineering Research Center of Metrology Instrument and System, Hebei University, Baoding 071002, China.

Nevertheless, due to the complicated meso-structure of 3D braided composites, it is difficult to sufficiently distinguish the damage and failure mechanisms from the traditional mechanical tests alone. Digital image correlation (DIC) is a non-contact optical testing method, which can accurately measure and calculate full-field displacements and strains at the surface of the objects under loading [9–12]. Feissel et al. [13] utilized DIC technique to study damage and rupture of 3D carbon/epoxy composites for detecting the evolution of early local nonlinear damage. Similarly, Zheng et al. [14] measured strain distribution for 3D braided carbon-aramid hybrid composites during tensile loading by DIC method. The surface full-field strain showed that high strain regions were distributed mainly over the yarns, while low strain zones were distributed along the resin. Meanwhile, Acoustic emission (AE) is a dynamic non-destructive testing (NDT) technology that has been successfully applied to detect the crack initiation and evolution of composites in real-time [15–17]. Su et al. [18] conducted a testing to distinguish all sorts of defects inside 3D braided composites by use of AE technology, the results indicated that the energy of AE signals in specimens with various defects were highly different. And the prefabricated defects caused the energy of AE signals increase in a certain corresponding range. Besides, compared with single NDT technology, the complementary method can achieve more comprehensive results. Nag-Chowdhury et al. [19] assessed the damage evaluation in glass fiber reinforced composites during incremental cyclic tensile tests by AE and DIC methods, which offered bright prospects to potentially anticipate the complete failure in composite structures. Hence, the complementary monitoring technology combining AE and DIC is more conducive to study the damage process of composites from inside to outside. Nevertheless, the research on the mechanical analysis of 3D braided composites by AE and DIC complementary technique is extremely limited.

In regard to the signal processing, AE method requires effective calibration and analysis to discriminate between all sorts of damage modes and failure mechanisms [20–22]. Meanwhile, the quantification of irreversible damage is a challenge and crucial aspect to understand the properties of materials, so it is necessary to find ways of quantifying the dynamic behaviors and micro-damage mechanisms [23–25]. Qi et al. [26] studied the randomly

microscopic events (RME) of acrylic bone cement materials under pure tension and three-point bending tests. It was demonstrated that AE statistical analysis approach with calculated amplitude distribution and probabilistic entropy can reveal the evolving process of the damage, which possibly foreshadow the failure of material. Zhou et al. [27] proposed a new method to distinguish multi-scale damage and failure process of fiber composites under mode-II delamination. The results indicated that AE statistical analysis approach reflects the inherent microscopic damage of fiber composites by the calculated amplitude distribution and amplitude spectrum. Kahirdeh and Khonsari [28] carried out numerous cyclic bending fatigue experiments on aluminum metals and glass/epoxy composites to study the process of micro-structural damage by the analysis of computed acoustic entropy. It was found that the features of acoustic entropy provided valuable damage information and quantified the deteriorations of materials. Thus, the statistical analysis method is effective to distinguish and quantify the history and evolution of micro-structural damage.

In this work, the effects of preform structures on longitudinal tensile behaviors of 3D carbon fiber braided composites were investigated systematically. Meanwhile, a novel statistical analysis method was firstly used for analyzing AE signals to distinguish and quantify the difference of various irreversible damage and failure mechanisms in 3D four directional and five directional braided composites. More importantly, the damage process and failure criteria for two types of composites based on computed deformation fields and AE signals were discussed.

2 Experimental details and methods

2.1 Specimens preparation

Two kinds of 3D carbon fiber braided composites with different preform structures were fabricated using the carbon fiber yarns (T700-12K) and epoxy resin matrix (TDE-86) through the resin transfer molding (RTM) technique by 3D braided machine in Jiangnan University. The specifications of two types of 3D braided composites are listed in Table 1.

Besides, Fig. 1 shows the geometry and dimensions of 3D braided composite specimens. Specimen A and B

Table 1 The specifications of two types of 3D braided composites

Type	Preform structure	Pitch length (mm)	Circumferential pitch length (mm)	Braiding angle (°)	Fiber volume fraction (%)
A	3D four directional	6.5–7.0	4.5	30°	55
B	3D five directional	6.8–7.0	3.8	30°	55

Fig. 1 The geometry and dimensions of 3D braided composite specimens

are 3D four directional and five directional carbon fiber braided composites, respectively. Meanwhile, for these two specimens, the average surface braiding angles are 30° , the fiber volume fractions are about 55% and the thickness of them are 5 ± 0.2 mm. Moreover, the inner unit cell models of 3D four directional and five directional braided composites are illustrated in Fig. 1a. It can be seen that the unit cell is a cube, which contains four kinds of braiding yarns with different directions for both specimen A and B. Besides, the specimen B has the additional axial reinforced yarns in longitudinal direction. And the interspace between the yarns is filled by matrix. In order to prepare the standard tensile samples, the 3D rectangular braided composite preforms with the dimensions of $305 \text{ mm} \times 305 \text{ mm}$ were cut into dog bone shape samples with a size of $200 \text{ mm} \times 25 \text{ mm}$ along longitudinal direction by cutting machine according to the ASTM D638 [29], the top and left view of the specimens are shown in Fig. 1b. Owing to the defects around the edge of specimens are inevitable, so the tensile experiments are applied on four samples for each type of preform structures to reduce the error of the cut-edge effect and free-edge effect [30, 31]. Besides, in order to avoid the damage of specimens from clamps, the aluminum stiffeners of size $40 \text{ mm} \times 25 \text{ mm}$ were glued on each side of the specimens. Finally, for purpose of obtaining the surface deformation field of Specimen A and B during tensile test, black/white speckles were sprayed in the center of specimens along the longitudinal and thickness directions about 70 mm, as depicted in Fig. 1c.

2.2 Tensile loading

The tensile experiments of 3D carbon fiber braided composites were conducted on LD26 tensile equipment at room temperature with a constant loading velocity 2 mm/min according to the standard of ASTM D3039 and GB/T 33613-2017 partly [32, 33]. Meanwhile, the speckle images and AE signals were acquired by two CMOS cameras (MER-500-7UM-L, $2592 \text{ pixels} \times 1944 \text{ pixels}$) and an AE instrument (AMSY-5, Vallen), respectively. The complementary NDT experimental system for tensile experiments is illustrated in Fig. 2.

Two resonant AE sensors (VS150-RIC, $100\text{--}450 \text{ kHz}$) with 34 dB inbuilt preamplifier and 150 kHz central frequency were used to record AE signals, whose distance was 70 mm. Silicone grease served as coupling agent, providing for good contact of the sensors and specimens. Moreover, lead-break tests were performed to ensure coupling before the experiments. To sufficiently eliminate mechanical and electrical noise, the threshold and sampling frequency of AE instrument were set to 5 mV (40 dB) and 5 MHz, respectively. Besides, the speckle images in front and side view of the specimens were collected twice every second by CMOS cameras during tensile tests. The deformed images for further analysis were scanned at 38 pixels/mm (front) and 35 pixels/mm (side).

2.3 Statistical analysis theory

The emergence of damage releases much of the energy, which is transmitted in the form of strain waves.

Fig. 2 Complementary NDT experimental system for tensile experiments

Meanwhile, extensive researches have confirmed that the strain waves are closely related to the physical properties of damage. AE technique is usually used to obtain the electrical signals of energy waves, and the corresponding AE signals are parallel to those released energy waves of damage [34, 35]. In order to further characterize and evaluate the dynamic response behaviors and invisible damage characteristics of 3D braided composites, the concept of damage field was proposed. And a multivariate of random damage is defined as a data matrix D^A in Eq. (1), which integrates four variables: M , N , i , and j [36, 37].

$$D^A = \{X_1, X_2, \dots, X_j, \dots, X_N\} = \begin{Bmatrix} Y_1 \\ \vdots \\ Y_i \\ \vdots \\ Y_M \end{Bmatrix} = [\alpha_{ij}]_{M \times N} = \begin{bmatrix} \alpha_{11} & \cdots & \alpha_{1j} & \cdots & \alpha_{1N} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{i1} & \cdots & \alpha_{ij} & \cdots & \alpha_{iN} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \alpha_{M1} & \cdots & \alpha_{Mj} & \cdots & \alpha_{MN} \end{bmatrix} \quad (1)$$

where M is the number of row vectors, which indicates the total quantities of observation windows that hinges on different time, load, or stress levels, and maximum of M is

dependent on the experimental results. In this work, we let the stress levels as the standard of observation window, due to the differences of preform structure for Specimen A and B. And i is the order of window sequence, $i = 1, 2, 3, \dots, M$. While N is the number of column vectors, which indicates the quantities of sub-intervals that depends on the desired accuracy and the total bandwidth of the AE characteristic parameters like amplitude, energy and other scalable parameters. The AE amplitude has been broadly used for its simplicity in characterization and damage assessment of composites among the acquired AE parameters [38, 39], so we associate the AE amplitude with the stress as the multi-scale criteria to obtain additional knowledge of the damage field. Besides, j is the order of sub-interval sequence, and $j = 1, 2, 3, \dots, N$.

The element α_{ij} is the number of RME from 0 to i , whose AE amplitude drops into j th sub-interval observed according to the measured stress, is expressed as:

$$\alpha_{ij} = \sum_{m=1}^i x_{mj} \quad i = 1, 2, 3, \dots, M, \quad j = 1, 2, 3, \dots, N \quad (2)$$

where x_i is an event of RME measured in the interval of $(i-1, i)$. So, the amplitude spectrum of RME is defined to describe the trends of the evolving damage state in materials. Moreover, the approximated Gibbs probability is given by:

$$p_{ij} = \alpha_{ij} / L_{ij} \quad (3)$$

and L_{ij} is to be:

$$L_{ij} = \sum_{j=1}^N \alpha_{ij} \quad (4)$$

Replacing α_{ij} with P_{ij} in Eq. (1), and the expression for probability space matrices of RME $\bar{D}^A$ is as follows:

$$\bar{D}^A = [P_{ij}]_{M \times N} \quad (5)$$

where the element P_{ij} denotes the probability distribution of AE signals, so the probability spectrum of RME $\bar{D}^A$ is a form of normalized amplitude spectrum matrix.

The entropy of a continuous probability is employed based on the Gibbs formula [40, 41]:

$$S := \int_0^1 \rho(x) \ln(1/\rho(x)) dx \quad (6)$$

where $\rho(x)$ is the Gibbs probability density function, let x represents an event of the AE amplitude measured on a scale. Moreover, $x=0$ corresponds exactly to the threshold of AE amplitude, and $x=1$ corresponds exactly to maximum amplitude, so according to x the N sub-intervals in ascending order used by the detector are $(0, 1/N], (1/N, 2/N], \dots, ((N-1)/N, 1]$.

The probability lies in the j th scale sub-interval is $P_{ij}(x) = \int_{(1/N)(j-1)}^{(1/N)j} \rho(x) dx$; then we can get $\rho_{ij}(x) = 1/(1/N) \int_{(1/N)(j-1)}^{(1/N)j} \rho(x) dx = N p_{ij}(x)$; and the approximated probability entropy is defined as [42]:

$$S \approx \sum_{j=1}^N (1/N) \rho_{ij}(x) \ln(1/\rho_{ij}) = \sum_{j=1}^N \rho_{ij}(x) \ln(1/(N p_{ij}(x))) \quad (7)$$

The minimum possible entropy value equals $\ln(1/N)$, which is achieved when all RME are in the same scale sub-interval. And the maximum possible entropy value equals 0 when all RME equally fall in every scale sub-interval. It is indicate that a greater uncertainty of RME occur with the increase of entropy; and the decreasing entropy means the increasing number of RME occur in few certain scales. The statistical analysis theory based on the calculated amplitude spectrum, probability distribution and entropy of AE signals is applied to 3D braided composites in the section below.

3 Results and discussions

3.1 Mechanical behaviors and damage characteristics

According to numerous tensile tests for 3D braided composite specimens with two kinds of preform structures, the

mechanical behaviors and damage characteristics were acquired. Furthermore, the tensile strength σ_f , which can be calculated by Eq. (8):

$$\sigma_f = F_s/bh \quad (8)$$

where F_s is the measured peak load, b and h are the width and thickness of the specimens, respectively. Table 2 shows the peak load and tensile strength for four groups of 3D braided composite specimens. As we can see, the average peak load and standard deviation of Specimen A are 10.25 and 0.64 kN, and those of Specimen B are 38.24 and 1.85 kN. Besides, the average tensile strength and standard deviation of Specimen A are 207.01 and 11.41 MPa, and those of Specimen B are 777.12 and 50.38 MPa. The calculation results indicate that 3D braided composite specimens have different load-bearing capacity under various preform structures, and Specimen B has much higher peak load and tensile strength than Specimen A.

Moreover, Fig. 3 exhibits tensile stress versus strain curves for 3D braided composite specimens. In the initial loading stage, firstly, the mechanical curves for Specimen A and B look like nearly unchanged, due to the increment rate of stress levels is relatively low. Then, the stress and strain curves for two types of composite specimens increase at a glacial pace. As the loading process keeps on, the curves increase smoothly and exhibit a similar linear relationship, gradually. When the specimens approach to fail, the stress reaches critical value. Afterward, the Specimen A and B fracture completely, the strength and stiffness of specimens decrease significantly, while the stiffness degradation rate of Specimen B is faster. Compared to Specimen B, the failure stress of specimen A is obviously lower, and the maximum strain is a little shorter. The results further indicate that the load-bearing capability of Specimen A differs with that of Specimen B, and Specimen B has better strength and enhanced elongation than Specimen A. It is because the introduction of axial reinforced yarns helps stabilise the structures in 3D five directional

Table 2 The load and strength for four groups of 3D braided composite specimens

Specimen	Peak load (kN)				Average value (kN)	Standard deviation (kN)
	1	2	3	4		
A	10.35	9.38	10.35	10.92	10.25	0.64
B	38.24	36.83	40.86	37.04	38.24	1.85
Specimen	Tensile strength (MPa)				Average value (MPa)	Standard deviation (MPa)
	1	2	3	4		
A	207.00	191.43	211.22	218.40	207.01	11.41
B	764.80	751.63	851.25	740.80	777.12	50.38

Fig. 3 Tensile stress versus strain for 3D braided composite specimens

braided composites, which strengthens the longitudinal tensile mechanical performances of Specimen B. Besides, the carbon fiber yarns have more excellent tensile strength and stiffness than softer polymer matrix, which take most of the applied load during the tests [43].

It can be found that the four groups of mechanical testing curves for 3D four directional and five directional braided composite specimens have a similar varying tendency. Meanwhile, the 3D braided composite specimens based on RTM technique will inevitably produce defects in manufacturing process, when the permeability of resin is inadequate [44]. The more compact preform structure with additional axial yarns introduction of Specimen B makes it difficult for the resin to infiltrate the fiber well, so the deviation of specimen B is a bit more than the one of Specimen A. While, the deviations of the stress versus strain curves for Specimen A and B are within a certain range. To better know the mechanical behaviors and damage mechanisms of 3D braided composites, two typical Specimen A and B are further studied in the following sections. The maximum stress of Specimen A and B is 218.40 and 740.80 MPa, and the maximum strain of them is 1.53 and 2.14% as shown in Fig. 3.

Figure 4 presents the final damage morphology of typical 3D braided composite specimens under tensile testing. It is clearly seen that the fracture of Specimen A is relatively plane and mainly concentrated on the upper side of the specimen, while Specimen B has a diagonal uneven fracture and the damage regions are in the middle to lower part of the specimen. Therefore, the macro-damage of specimen B is much more obvious than that of specimen A. Moreover, Fig. 5 shows the compositions and structures of 3D braided composite specimens. It can be seen that an interface of 3D four directional or five directional braided

Fig. 4 The final damage morphology of typical 3D braided composite specimens under tensile testing

composite is composed of yarns and out-of-yarn matrix. Besides, the yarn contains a bundle of fibers and their surrounding in-yarn matrix [45, 46].

Fig. 5 The compositions and structures of 3D braided composite specimens

In order to further understand the meso-scale and micro-scale damage and failure modes of specimens, the two types of fractured composite specimens were further observed by a digital microscope (SK2700P). It can be observed that the damage modes near the fractures for both Specimen A and B are interface damage, matrix cracking, fiber/matrix debonding and fiber breakage in front and side view of the damaged composites. However, the damage regions and damage degrees are much more obvious in Specimen B as compared to Specimen A, and larger quantities of matrix cracking and fiber breakage occur in Specimen B. The cause of this phenomenon is that the additional axial yarns embedded amongst interlaced braiding yarns for 3D five directional braided composites, which helps Specimen B own much more yarns and have a more compact space structures than Specimen A. Besides, the ultimate breakage of a large number of axial and braiding yarns releases mass energy, thus resulting in relatively larger failure load and more obvious damage in 3D five directional braided composites [47, 48]. According to the results observed by digital microscope, the damage characteristics from the physical mechanisms have been put forward. The real-time damage progress detection of 3D braided composite specimens will be analyzed according to the AE and DIC methods, later.

3.2 Characteristics of AE signals

In this work, we selected two respective 3D braided composite specimens with different preform structures to study AE signal characteristics during the tensile testing. Figure 6 exhibits the AE amplitude and cumulative hits versus time for two types of specimens. Moreover, the

corresponding AE amplitude and stress versus strain for 3D braided composite specimens is shown in Fig. 7.

1. In the initial stage, firstly, no signal is detected and the stress is very low, which indicates that there is no damage and the specimens are in a completely elastic state. Then, a few AE signals with low amplitude (from 40 to 50 dB) are obtained as the time and strain increases up to 10 s and 0.17% or so, respectively. Meanwhile, the cumulative hits and stress rise slowly, revealing the major damage modes of Specimen A and B are most probable internal manufacturing defects and interface micro-cracks of 3D braided composites under low load condition at this stage [49].
2. In the evolution stage, as stress increases, larger quantities of AE signals and cumulative hits are generated than the initial stage. This phenomenon shows that the damage degrees increase significantly. For Specimen A in Figs. 6a and 7a, it can be found that the amplitude is mainly concentrated in 40–80 dB, which suggests that the major damage modes like matrix cracking and fiber/matrix debonding may gradually occur [27]. Moreover, few high amplitude (from 80 to 100 dB) AE signals are generated, indicating the emergence of fiber breakage in Specimen A [50]. By contrast, the Specimen B shown in Figs. 6b and 7b experiences a similar phenomenon to Specimen A, and whereas much higher stress and much more AE events appear in Specimen B during this stage. It is demonstrated that the damage arises much obviously in Specimen B.
3. In the failure stage, the number of AE signals and cumulative hits increases rapidly, which indicates the dramatic exacerbation of materials. Meanwhile, the total range of AE amplitude is from 40 to 100 dB for

(a) Specimen A(Three dimensional four directional)

(b) Specimen B(Three dimensional five directional)

Fig. 6 The amplitude and cumulative hits versus time for 3D braided composite specimens

(a) Specimen A(Three dimensional four directional)

(b) Specimen B(Three dimensional five directional)

Fig. 7 The amplitude and stress versus strain for 3D braided composite specimens

Specimen A and B, so the composites are accompanied by multiple damage modes like matrix cracking, fiber/matrix debonding and fiber breakage. Moreover, more high amplitude (from 80 to 100 dB) AE signals are observed, indicating that the fiber damage is much severer in this stage. When the stress of Specimen A reaches maximum as shown in Fig. 7a, the specimen fractures completely and releases a large amount of energy. Meanwhile, the cumulative hits of Specimen A reaches peak in Fig. 6a, as well. Besides, when the time and strain of Specimen B increase up to 120 s and 1.53% or so, the stress and the cumulative hits reach the first peak value indicating that the specimen approaches damage tolerance. Then, the stress curve has a slight drop and only high amplitude (from 80 to 100 dB) AE signals are generated as depicted in Figs. 6 and 7b, which indicates that axial and braiding yarns cannot carry the heavy load, resulting in numerous fiber failure. Afterwards, the stress and cumulative hits reach maximum, the Specimen B is completely broken. Comparing with the Specimen A in Figs. 6a and 7a, more AE signals with high amplitude and cumulative hits of Specimen B appear as illustrated in Figs. 6b and 7b. This phenomenon further demonstrates that much more obvious damage is induced in Specimen B, which is in accord with the final damage morphology in Fig. 4. In order to further reflect the dynamic response behaviors of AE signals, distinguish and quantify various types of irreversible damage and failure mechanisms, the AE statistical analysis method was studied in detail.

3.3 Statistical analysis of AE signals

The mechanical data and AE data of 3D braided composites are analyzed based on C++ language. Meanwhile, the schematic diagram of damage state measurement and probability entropy calculation according to statistical analysis theory is shown in Fig. 8.

Fig. 8 The schematic diagram of statistical analysis method

And the process of the statistical analysis method is as follow: Firstly, input the mechanical data and AE data of 3D braided composites. Besides, initialize the number of stress observation windows M and AE amplitude sub-intervals N . Secondly, search for the maximum stress and divide the stress into M stages. Thirdly, extract the information of AE data and divide the amplitude into N equal sub-intervals. The next step is to combine stress levels with AE amplitude based on the corresponding time. Then, count the number of AE events and probability in every amplitude sub-intervals at various stress levels. In the end, calculate the probability entropy of AE events and output data.

For 3D four directional and five directional braided composite specimens, there were no detectable AE signals at or below 40 dB before the tensile tests, so the threshold of AE system was set to 40 dB. Meanwhile, the maximum amplitude of Specimen A and B during the tests were approach to 100 dB. Therefore, the measured amplitude range of acquired RME for Specimen A and B were in the interval from 40 to 100 dB. In this work, we use $N=6$, so the interval is divided into six equal sub-intervals, and each of them is from $40 + 10(j-1)$ to $40 + 10j$ dB ($j=1, \dots, 6$), and the RME amplitude bandwidth are 10 dB. The amplitude spectrum at various stress levels for typical 3D braided composite specimens is shown in Fig. 9. Each individual spectrum quantifies a damage state at corresponding applied stress levels, and the mode of every amplitude spectrum is one of the important factors of the association between RME occurred at various stress levels.

It is found that AE events with low amplitude are dominant in initial stage and the main damage is small scale micro-damage of 3D braided composites. As the applied stress increases, AE events with higher amplitude continuously occur and gradually form bigger bandwidth of

amplitude spectrum, which corresponds to the increasing occurrence of damage. When the applied stress increases up to 100 MPa for Specimen A and 200 MPa for Specimen B, the amplitude spectrum ranges from 40 to 90 dB. While the stress is 130 MPa for Specimen A and 340 MPa for Specimen B, the amplitude spectrum ranges from 40 to 100 dB. Meanwhile, the AE events emerge in the highest amplitude sub-interval, and the entire bandwidths of amplitude spectrum are gradually formed. This transitional zones appear between 100 and 130 MPa for Specimen A, and between 200 and 340 MPa for Specimen B. Then, we can see an altered shape of AE amplitude distribution, which indicates numerous new damage modes arise. Afterward, AE events with larger amplitude increase, indicating more RME occur in the highest amplitude sub-interval. Furthermore, from the general tendency of amplitude spectrum, the number of AE signals with low amplitude is more than that with high amplitude. Besides, as the increase of amplitude in every observation window at corresponding stress levels, the number of AE events decrease obviously. The tendency agrees well with that in Figs. 6 and 7. Once the stress approaches to maximum, the quantities of AE events increase apparently, but the amplitude spectrum has no obvious change in shape. This phenomenon indicates that the degree of damage increases significantly, while no new damage mode is induced. The distribution of amplitude spectrum in Fig. 9b is similar to that in Fig. 9a, but the total quantities of AE events in Specimen A are lower than that in Specimen B. This can be attributed to more obvious damage of 3D five directional braided composites, which is associated with the final damage morphology in Fig. 4.

Figure 10 exhibits the approximated Gibbs probability distribution of AE events at various stress levels for the typical 3D braided composite specimens. It is demonstrated

Fig. 9 The amplitude spectrum at various stress levels for 3D braided composite specimens

Fig. 10 The approximated Gibbs probability distribution of AE events at various stress levels for 3D braided composite specimens

that the probability of RME with low amplitude is obviously bigger than those of high amplitude, only an exception in Fig. 10a, which agrees well with the distribution of amplitude spectrum in Fig. 9. The phenomenon shows that the damage corresponding to the AE events with lower amplitude is continued occurrence during the whole tensile process and the damage modes in the initial stage have more uncertainty. Once the whole spectral region is formed, for each selected stress levels, the probability distribution is in the form of an exponential function [51], it is inferred that the uncertainty of damage has a slight decrease. As the applied stress is near to the breaking point, the probability distribution is almost unchanged, revealing the damage develops in a certain direction. Thus,

the normalized Gibbs probability distribution can further describe damage state of RME.

Figure 11 presents the probability entropy of AE events at various stress levels for 3D braided composite specimens. To increase the accuracy of the calculated entropy, the number of equal sub-intervals of amplitude is set to 60. So, the total bandwidth of the amplitude spectrum for Specimen A and B are 60 dB. Besides, the number of the observation window of stress in Fig. 11a, b is set to 22 and 37, respectively. Hence, for Specimen A, $M=22$, $N=60$, the entropy is observed every 10 MPa, while Specimen B is observed every 20 MPa, and $M=37$, $N=60$. Overall, the damage process can be split into the following three stages:

Fig. 11 The probability entropy of AE events at various stress levels for 3D braided composite specimens

1. At the initial damage stage (from O to B), firstly, there is no AE events with amplitude over 40 dB, the entropy of Specimen A and B is 0. As we can see, when stress increases up to 30 MPa (point A in Fig. 11a), all acquired RME fall in the same scale sub-interval, the entropy of Specimen A reaches the minimum, $S = -4.09$. Similarly, at around 80 MPa (point A in Fig. 11b), the least entropy of Specimen B appears, that is about $S = -3.40$. Then, the entropy begins to increase linearly (from A to B, $ds/d\sigma \approx \text{constant} > 0$), which corresponds to the existence of AE events with higher amplitude and some uncertain small-scale damage in internal and interface of 3D braided composites under low loading condition.
2. At the damage evolution stage (from B to E), as the stress increases, the growth rate of entropy has gradually decreases (from B to C, $ds/d\sigma > 0$, $d^2s/d\sigma^2 < 0$), revealing the appearance of new damage modes and a slight drop of uncertain damage may be accompany by matrix cracking and fiber/matrix debonding of 3D braided composites. When the stress increases from 100 to 120 MPa (from C to D in Fig. 11a), the slope of Specimen A is approximately 0 ($ds/d\sigma \approx 0$). Meanwhile, as the stress increases from 160 to 280 MPa, (from C to D in Fig. 11b), the entropy of Specimen B is approximately constant or with a slight downward ($ds/d\sigma \leq 0$). The results indicate that the responses of inherent microscopic structure under the applied stress are nearly identical and no new damage modes arise. Afterwards, the entropy has a linear increase (from D to E, $ds/d\sigma \approx \text{constant} > 0$), then the detected AE events start to emerge in all 60 sub-intervals, resulting in the formation of the entire spectrum bandwidth (point E). This transition is related to the change in shape of the curves as shown in Fig. 9, the amplitude distribution includes an apparently larger occurrence of high amplitude signals, indicating that besides matrix cracking and fiber/matrix debonding, a small amount of fiber breakage occurs at this stage as well.
3. At the failure stage (from E to G), the entropy significantly increases ($ds/d\sigma > 0$), which is consistent with the increasing number of RME, meaning the uncertainty of damage state increases rapidly and multiple damage modes occur during this stage. Meanwhile, the more and more severe damage like fiber failure starts to emerge and evolve. When the stress approximates to peak value, the entropy increases up to maximum and the variation of entropy remains unchanged or minimum (from F to G), meaning the damage state maintains almost constant and the number of RME grow evidently in few certain scales. Compared to Specimen A, the entropy of Specimen B is a little larger

at this damage stage. The phenomenon further indicates that the final damage is much more obvious in 3D five directional braided composites, which is associated with the mechanical and damage characteristics of 3D braided composites.

Therefore, the use of probability entropy can well reveal the state and evolution of the randomly generated damage modes during the tensile tests. The statistical analysis of AE signals with amplitude spectrum, normalized probability distribution and probability entropy can be used as criterion quantitatively to distinguish and quantify various types of irreversible damage and failure mechanisms in 3D braided composites.

3.4 Distribution of strain fields

The two dimensional DIC method was adopted for measuring the full-field strain distribution at surface of the investigated 3D braided composite specimens by searching for the maximum correlation coefficient C between the reference images f and deformed images g . Moreover, the correlation coefficient $C(u, v)$ can be expressed by Eq. (9):

$$C(u, v) = \frac{\sum_{i=1}^m \sum_{j=1}^m [f(x_i, y_j) - \bar{f}] [g(x'_i, y'_j) - \bar{g}]}{\sqrt{\sum_{i=1}^m \sum_{j=1}^m [f(x_i, y_j) - \bar{f}]^2} \sqrt{\sum_{i=1}^m \sum_{j=1}^m [g(x'_i, y'_j) - \bar{g}]^2}} \quad (9)$$

Here, $f(x, y)$ is the gray value of the reference image and $g(x', y')$ is the gray value of the deformed image. $\bar{f}$ and $\bar{g}$ are the average gray value of $f(x, y)$ and $g(x', y')$, respectively. During the tensile tests, the strain in the vertical direction ε_y at different stress levels was calculated exactly by the DIC processing software, which is based on the gray scale distribution of digital images [50–52].

Figures 12 and 13 show the front view of vertical strain distribution for Specimen A and B at specific stress levels, respectively. As illustrated in Fig. 12, when the stress increases from 70 to 80 MPa, 130 to 140 MPa and 170 to 180 MPa, the maximum strain in vertical direction of Specimen A is 0.010000, 0.012500 and 0.017000 ε , respectively. Meanwhile, the corresponding average strain is 0.000438, 0.000496 and 0.000754 ε . For Specimen B, an obvious change can be observed from Fig. 13a–c. As the stress increases from 170 to 180 MPa, 530 to 540 MPa and 690 to 700 MPa, the maximum vertical strain value is 0.002760, 0.004220 and 0.024200 ε , respectively. Correspondingly, the average strain is 0.000134, 0.000276 and 0.000353 ε , as summarized in Table 3.

Furthermore, Figs. 14 and 15 exhibit the side view of vertical strain distribution for Specimen A and B at specific stress levels, respectively. As shown in Fig. 14, when

Fig. 12 The front view of vertical strain distribution for Specimen A at specific stress levels **a** 70–80 MPa, **b** 130–140 MPa and **c** 170–180 MPa, respectively

Fig. 13 The front view of vertical strain distribution for Specimen B at specific stress levels **a** 170–180 MPa, **b** 530–540 MPa and **c** 690–700 MPa, respectively

Table 3 The vertical strain values (front) for Specimen A and B at different stress levels

Front	Specimen A			Specimen B		
Vertical	70–80 MPa	130–140 MPa	170–180 MPa	170–180 MPa	530–540 MPa	690–700 MPa
$\max \epsilon_y, \epsilon$	0.010000	0.012500	0.017000	0.002760	0.004220	0.024200
$\overline{\epsilon_y}, \epsilon$	0.000438	0.000496	0.000754	0.000134	0.000276	0.000353

Fig. 14 The side view of vertical strain distribution for Specimen A at specific stress levels **a** 70–80 MPa, **b** 130–140 MPa and **c** 170–180 MPa, respectively

the stress of Specimen A increases from 70 to 80 MPa, 130 to 140 MPa and 170 to 180 MPa, the maximum vertical strain is 0.003100, 0.005720 and 0.007500 ϵ , respectively. Meanwhile, the corresponding average strain is 0.000444, 0.000649 and 0.000850 ϵ . From Fig. 14a–c, when the stress increases from 170 to 180 MPa, 530 to 540 MPa and 690 to 700 MPa, the maximum strain value of Specimen B is 0.004800, 0.012800 and 0.066500 ϵ , respectively. Correspondingly, the average strain is 0.000144, 0.000155 and 0.000516 ϵ , as listed in Table 4.

According to the strain analysis results, it can be found that the vertical strain value in the front and side direction of Specimen A and B become larger, as the stress increases at same increment. Furthermore, the number of AE signals also increases gradually as illustrated in Figs. 6 and 7. When the stress increases from 70 to 80 MPa for Specimen A and 170 to 180 MPa for Specimen B, it can be seen that the range of AE amplitude and the rate of AE cumulative hits are relatively low. As the stress increases from 130 to 140 MPa for Specimen A and 530 to 540 MPa for Specimen B, the AE events emerge in every amplitude range and there is a slight increase of the rate of AE cumulative hits. And at the last stage from 170 to 180 MPa for Specimen A and 690 to 700 MPa for Specimen B, larger quantities of AE signals emerge and the rate of AE cumulative hits

increases significantly. The remarkable increase of strain in loading direction and the number of typical AE characteristic parameters indicates that the yarns and matrix are increasingly damaged, leading to the reduction of carrying capacity of composites. By contrast, the average strain level of Specimen B is a little lower than that of Specimen A at the same stage of tensile testing, further indicating that the more compact fiber perform architectures in Specimen B increases the deformation resistibility capacity of 3D five directional braided composites [53, 54].

Moreover, it is clearly observed that the distribution of strain fields for both Specimen A and B are all inhomogeneity and scattered in blocks of irregular shape, which further proves the structural complexity and mechanical anisotropy of 3D braided composite [55, 56]. Once the applied stress approaches to maximum as shown in Figs. 12c–14c, the strain in vertical direction grow substantially. Meanwhile, as we can see from Figs. 6 and 7, the corresponding AE signals are adequate at this critical moment and some high amplitude signals are generated and AE cumulative hits increase rapidly, as well. Besides, the maximum failure-to-strain of Specimen B is much higher than that of Specimen A. It also demonstrates the peak stress and tensile strength are higher in Specimen B. In addition, an obvious local strain concentration in loading direction

Fig. 15 The side view of vertical strain distribution for Specimen B at specific stress levels **a** 170–180 MPa, **b** 530–540 MPa and **c** 690–700 MPa, respectively

Table 4 The vertical strain values (side) for Specimen A and B at different stress levels

Side	Specimen A			Specimen B		
	70–80 MPa	130–140 MPa	170–180 MPa	170–180 MPa	530–540 MPa	690–700 MPa
max ϵ_y, ϵ	0.003100	0.005720	0.007500	0.004800	0.012800	0.066500
$\bar{\epsilon}_y, \epsilon$	0.000444	0.000649	0.000850	0.000144	0.000155	0.000516

of Specimen B can be observed in Figs. 13c and 15c, revealing more obvious final damage in 3D five directional braided composites.

To sum up, the diversification of side strain distribution is consistent with that of front strain distribution. And the analysis results measured by DIC method are associated well with the characteristics of AE signals discussed in previous. Therefore, the variation of strain fields measured the deformation at surface of the specimens and AE technology describes the damage evolution of 3D braided composites, providing failure criterion for braided composites.

4 Conclusions

In summary, numerous tensile tests were carried out for simultaneously monitoring the mechanical behaviors and damage properties of 3D four directional and five

directional braided composites based on AE and DIC analysis methods. It can be found that the more compact perform structure with additional axial reinforced yarns of 3D five directional braided composites increases longitudinal load-bearing and deformation resistibility capacity. Besides, both two kinds of 3D braided composites exhibit graceful failure, while the damage modes like interface damage, matrix cracking, fiber/matrix debonding and fiber breakage are much more obvious in 3D five directional braided composites, due to huge energy release from the ultimate breakage of a large number of axial and braiding yarns. Furthermore, the AE signals collected during tensile process were post processed by statistical analysis method in detail. According to the amplitude spectrum, normalized probability distribution and probability entropy, the evolving irreversible damage state of 3D braided composites during tensile tests were recognized and assessed successfully. Therefore, by the use of statistical analysis

method, the failure criterion of braided composites can be established and developed effectively. Meanwhile, the deformation and damage evolution of specimens are further monitored by AE and DIC methods, which provides damage and failure criterion for two types of composites. As for the future studies, the effect of other important factors such as braiding angles or other braiding parameters, temperature, and the free-edge effect of specimen will be investigated to further reveal the mechanical and damage behaviors of 3D braided composites.

Acknowledgements The authors of this paper wish to acknowledge the financial support of the National Natural Science Foundation of China (Grant Nos. 11502064 and 11572109).

Compliance with ethical standards

Conflict of interest The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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