Damage mechanisms assessment of hybrid carbon/flax fibre composites using acoustic emission

Mariam Ben Ameer^{1,2,*}, Jean-Luc Rebiere¹, Abderrahim El Mahi¹, Moez Beyaoui², Moez Abdennadher², and Mohamed Haddar²

¹Le Mans Université, Laboratoire d'acoustique de l'université du Mans (LAUM), UMR CNRS 6613, Av. O. Messiaen 72085 Le Mans Cedex 9, France

²Ecole Nationale d'Ingénieurs de Sfax, Département Génie Mécanique, Laboratoire de recherche de Mécanique, Modélisation et Production (LA2MP), Route Soukra, 3038 Sfax, Tunisie

Abstract. The purpose of the present experimental study is to describe the damage mechanisms occurring in epoxy matrix composites reinforced with hybrid carbon-flax fibres. The samples tested were consist of unidirectional carbon and flax fibre plies with different stacking sequences. Composite laminates were manufactured by hand lay-up process. The specimens were tested under uniaxial tensile loading. The tests carried out were monitored by the acoustic emission (AE) technique. The results obtained during the monotonic tensile tests were analyzed in order to identify the damage mechanisms evolutions. The recorded events were classified with the k-means algorithm which is a statistical multivariable analysis. In addition, it was an unsupervised classification according to temporal descriptors. The percentage of each damage mechanism to the global failure was evaluated by the hits number and the acoustic energy activity. The AE technique was correlated with scanning electron microscopy (SEM) observations to identify the typical damage mechanisms.

1 Introduction

Recently, researchers have become increasingly interested in the use of bio-based composites. Composites reinforced with natural fibres are ecological, biodegradable, their availability is unlimited and they have a relatively interesting specific property. Therefore, plant fibres can be an alternative to synthetic ones [1]. Flax fibre reinforced composites are the most interesting bio-based composites that have been studied. Their mechanical characteristics are the subject of the work of Monti et al. [2]. Also, they identify the occurred damage mechanisms by the acoustic emission (AE) technique. In addition to the mechanical properties, dynamic properties have become an important factor for high performance applications. Duc et al. [3] studied the mechanical and dynamic properties of glass, flax and carbon fibre composites. They found that flax fibre composites have higher performance for damping behaviour, but poor mechanical properties compared to carbon fibre composites.

In order to improve the dynamic properties of carbon fibre composites, recent studies have proposed the development of hybrid composites with carbon and flax fibres [4]. Ben Ameer et al. [5] evaluated the damping properties of hybrid carbon-flax fibre composites. Flynn et al. [6] studied the mechanical behaviour of carbon-flax hybrid composites. These hybrid composites may have different damage mechanisms which occur when they are

under service loading. For hybrid glass-flax composites, Saidane et al. [7] investigated the damage mechanisms by using the acoustic emission (AE) technique.

In this context, the objective of this work is to investigate the failure mechanisms occurring under static tensile loading on unidirectional composites reinforced by carbon and flax fibres. An AE damage analysis is presented. This identification is made with the k-means algorithm which is an unsupervised classification with a multivariable statistical technique. A discrimination of the damage mechanisms was made by using the AE amplitude range, vector of hits and contribution of the AE energy. Finally, SEM images of failed specimens are correlated with the AE classification to identify the existing damage mechanisms.

2 Materials and processing

The materials studied are carbon fibre laminates, flax fibre laminates and flax / carbon hybrid fibre laminates. These materials are made from a unidirectional carbon fibre fabric and a unidirectional Flax tape fibre supported in a SR 1500 epoxy resin mixed with an SD 2505 hardener. The density of carbon and flax fibres were 300 g / m² and 200 g / m², respectively. The different stacking sequences consist of 6 layers oriented in the direction of fibres. They are shown in Table 1. The composite plates were manufactured using a vacuum moulding process.

* Corresponding author: [Mariem.Ben_Ameer.Etu@univ-lemans.fr](mailto:Mariam.Ben_Ameer.Etu@univ-lemans.fr)

They were cured at room temperature (20 ° C) and at a pressure of 50 kPa for 7 hours.

Rectangular test pieces having a length of 200 mm and a width of 15 mm were cut with a high-speed diamond saw. In order to avoid moisture absorption, no lubricating fluid was used when cutting parts. After cutting, the edges were lightly polished with fine sandpaper.

3 Experimental procedure

Static tensile tests were performed on non-hybrid and hybrid laminates until failure. They were carried out on a servo hydraulic machine equipped with a 100 kN load cell. Specimens were tested according to the standard test method ASTM D3039/D3039 M. In order to investigate the different damage mechanisms within the studied materials, it is very useful to apply non-destructive technique during mechanical tests such as the AE. Generally, AE data can be inspected and analysed by the waveform-based analysis or parameter-based analysis. They were processed using NOESIS software [8]. Five temporal parameters were selected for the classification of the acoustic emission signals: amplitude, rise time, duration, number of counts to peak and energy. They are illustrated in Fig. 1.

For each specimen, microscopic observations of the failure mode were achieved. In fact, scanning electron microscopy (SEM) was used to detect smaller damage mechanisms of failure profiles.

Fig. 1. Acoustic emission burst features.

4 Results and discussion

4.1 Microscopic observations

Fig. 2 presents the SEM images of fractured surfaces for the carbon and flax specimens. Matrix cracking was observed in Fig. 2a and Fig. 2c label 1. Generally, it appears to be the propagation of initial cracks at the interface of flax bundles and matrix or carbon fibres and matrix. In addition, debonding between fibre and matrix can be observed for the flax laminates and carbon laminates in Fig. 2b and Fig. 2d label 2. These failed specimens also exhibited delamination between plies. Several fibres pull-outs can also be noticed (Fig. 2a and Fig. 2d label 3) either in the form of fibres leaving the

matrix, or in the form of holes in the latter. Finally, we observe the fibre breakage in Fig. 2b and Fig. 2d.

Fig. 2. SEM observations of failure profiles: a) and b) for flax fibre laminates, c) and d) for carbon fibre laminates.

4.2 Amplitude range

The classification applied on the non-hybrid and hybrid laminates enabled us to identify four damage mechanisms according to their acoustic signature and amplitude ranges: matrix cracking (class A), fibre-matrix debonding (class B), delamination (class C) and fibre pull-out and fibre failure (class D). These damage mechanisms were attributed by analysing the waveform of each class, as well as the contribution of the AE parameters as reported in [2,9]. In addition, they were attributed by a correlation with the existing damage mechanisms observed by SEM observations.

Fig. 3. Amplitude ranges of AE signals versus the four class for non-hybrid and hybrid composites.

Fig. 3 presents the amplitude ranges of AE signals according to the four classes for non-hybrid and hybrid flax-carbon laminates. The results obtained for non-hybrid materials are almost similar to hybrid materials. It is important to note that the AE signals induced by the matrix cracking are characterised by low amplitudes,

centred around 42 dB. The AE signals induced by fibre-matrix debonding were identified by signals of amplitudes, centred about 50 dB for non-hybrid and hybrid materials. In addition, delamination between fibre layers, was detected,

Finally, the amplitudes of signals induced by the fibre failure were detected by median values of about 65 dB and reach 77 dB and 100 dB for flax fibre and carbon fibre laminates, respectively. This amplitude offset is explained by the difference of rigidity between flax and carbon fibres.

4.3 cumulative Hits

Once the damage mechanisms are characterized, the time of occurrence of each acoustic event is stored. As shown in Fig. 4, matrix micro-cracks (Class A) are the most dominant damage mechanisms for all the stacking sequences. They appear from the start of the test and propagate until the final failure of the specimen. This damage mechanism corresponds to more than 40% of the AE signals collected during static tests. Debonding between fibre/matrix (Class B) is the second damage mode that appears after matrix cracking. The number of events corresponding to fibre/matrix debonding increases continuously until failure of the specimen.

Fig. 4. Cumulative number of vector of hits for all specimens: a) $[F_3]_s$, b) $[F_2/C]_s$, c) $[F/C_2]_s$ and d) $[C_3]_s$.

The class contains signals with amplitude between 50 and 65 dB, which appear just after fibre/matrix debonding, are resulting from delamination mechanism (Class C). They are developed in the interface of adjacent plies. At 50% of the load of the tests, signals began to be detected where represent fibre pull-out and fibre breakage (Class D). It's observed that the highest number of hits is recorded in the case of carbon composite laminates (Fig.

5). This fact can be explained by the augmentation of the rigidity with carbon fibres and then with the augmentation of the applied load

Fig. 5. Comparison between the global number of vector of hits for the studied laminates for each class.

4.4 Energy contribution

In this section, Fig. 6 presents the absolute energy ranges of AE signals according to the four classes for non-hybrid and hybrid flax-carbon laminates. The results obtained for hybrid materials are almost between those of non-hybrid materials. Similarly to the amplitude range, the absolute energies of damage mechanisms of class A are the lowest ones and for Class D are the highest ones. In addition, it is clearly observed that the energy of class D for carbon fibre is very higher than that of flax fibre laminates.

Fig. 6. Absolute energy ranges of AE signals versus the four class for non-hybrid and hybrid composites.

For the evaluation of the contribution of each damage mechanism to the global failure of the studied composites, it was defined the damage contribution factor (DC). This factor was calculated by the cumulative AE energy of a given mode (E_i) divided by the total cumulative AE energy at failure (E_T) according to [10]:

$$D_i = \frac{E_i}{E_T} = \frac{E_i}{\sum_{j=1}^n E_j} \quad (1)$$

The relative contribution D_i for each damage mechanism in terms of energy to the final failure for all studied specimens was reported in Fig. 7. A clear

similarity in the D_i distribution is observed for all types of composites. It is evident that the most significant energy mechanism was for the fibre pull-out and the fibre breakage, with more than 72% of contribution for flax laminates and reach more than 90% for carbon laminates. Indeed, the failure of fibres generates a higher absolute energy may be caused by the important stiffness of fibres.

Fig. 7. Damage mechanisms contribution by the AE energy for the four studied materials.

5 Conclusion

The aim of this work is to investigate the damage mechanisms of hybrid flax-carbon fibre composites, using acoustic emission technique. The composites, composed of unidirectional flax and carbon fibre plies with different stacking sequences, were subjected to tensile test. From AE signals, the clustering methodology combined with SEM observations allowed us to identify four damage mechanisms: matrix cracking, fibre-matrix debonding, delamination and fibre pull-out and fibre failure. The results obtained showed that, although the event numbers associated to the fibre breakage was the lowest, their contribution to the overall failure of composites was the predominant regarding to the cumulative of AE energy.

We would like to thank Isabelle Gimenez from CTM (Centre de Transfert de Technologie du Mans) for her help with the electronic microscopic observations.

References

1. P. Wambua, J. Ivens, I. Verpoest, Compos. Sci. Technol. **63**, 1259–64 (2003).
2. A. Monti, A. El Mahi, Z. Jendli, et L. Guillaumat, Compos. Part Appl. Sci. Manuf., **90**, 100–110 (2016).
3. F. Duc, P.E. Bourban, J.A.E. Manson, Compos. Part Appl. Sci. Manuf., **64**, 115–23 (2014).
4. H. N. Dhakal, Z. Y. Zhang, R. Guthrie, J. MacMullen, et N. Bennett, Carbohydr. Polym., **96**(1), 1–8, (2013).
5. M. Ben Ameer, A. El Mahi, J.-L. Rebiere, M. Abdennadher, et M. Haddar, Int. J. Appl. Mech., **10**(05), 1850050 (2018).

6. J. Flynn, A. Amiri, C. Ulven, Mater. Des. **102**, 21–29 (2016).
7. E. H. Saidane, D. Scida, M. Assarar, et R. Ayad, Compos. Struct., **174**, 1–11 (2017).
8. S. KATTIS, « *Noesis - Advanced Data Analysis, Pattern Recognition & Neural Networks Software for Acoustic Emission Applications* », p. 8.
9. S. Masmoudi, A. El Mahi, et S. Turki, Compos. Part B Eng., **80**, 307–320, (2015).
10. A. Bravo, L. Toubal, D. Koffi, et F. Erchiqui, Mater. Des. **66**, 16–28, (2015).