



HAL
open science

TOWARDS INTEGRATED HEALTH MONITORING OF BIO-BASED COMPOSITE STRUCTURES: INFLUENCE OF ACOUSTIC EMISSION SENSOR EMBEDMENT ON MATERIAL INTEGRITY

Guillem Seychal, Xavier Gabrion, Emmanuel Ramasso, Gilles Bourbon,
Patrice Le Moal, Vincent Placet

► **To cite this version:**

Guillem Seychal, Xavier Gabrion, Emmanuel Ramasso, Gilles Bourbon, Patrice Le Moal, et al.. TOWARDS INTEGRATED HEALTH MONITORING OF BIO-BASED COMPOSITE STRUCTURES: INFLUENCE OF ACOUSTIC EMISSION SENSOR EMBEDMENT ON MATERIAL INTEGRITY. 1, pp.839-847, 2022, 978-2-9701614-0-0. hal-03956072

HAL Id: hal-03956072

<https://hal.science/hal-03956072v1>

Submitted on 25 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

TOWARDS INTEGRATED HEALTH MONITORING OF BIO-BASED COMPOSITE STRUCTURES: INFLUENCE OF ACOUSTIC EMISSION SENSOR EMBEDMENT ON MATERIAL INTEGRITY

Guillem SEYCHAL^a, Xavier GABRION^a, Emmanuel RAMASSO^a, Gilles BOURBON^a, Patrice LE MOAL^a, Vincent PLACET^a

a: Université Franche-Comté - FEMTO-ST Institute - Dept Applied Mechanics (Besançon, FR)

Abstract: *Structural Health Monitoring (SHM) and Natural Fibres Composites (NFC) have lived since early 2000's important progress due to the needs of reducing material consumption and weight in operating structures while limiting the environmental footprint and increasing the safety of such structures. Acoustic Emission (AE) is one of the numerous solutions that appears to be suitable to predict service life and assess damage in composite structures. NFCs have shown promising properties for structural applications but their complex behaviour and the limited knowledge on their long-term durability still hinder their full development. In that sense, AE-based SHM could allow a more important breakthrough of bio-based composites by monitoring damage evolution and assessing their remaining life in service conditions. The new generation of AE-sensors offers also opportunities of embedment thanks to their smaller size, leading to better protection of the sensors and increased sensitivity. We propose in this work to study the effect of the embedment of millimetric-size dummy sensors in flax/epoxy laminates on the monotonic tensile behaviour and damage kinetic up to failure through AE methods. Results highlight a limited effect of the presence of dummy sensors on the mechanical behaviour and properties. AE results coupled with X-ray tomography pictures however highlight a change in location of damages that are more likely to append in the insert vicinity, and in the onset of the most severe damages, which appears at lower global deformation levels.*

Keywords: Natural fibres; Mechanical properties; Acoustic emission; Smart materials; Biobased Composites

1. Introduction

Natural fibre composites have known an important development over the last two decades. These fibres have shown promising properties [1], competitiveness and process have been enhanced so far that structural biobased composites are now a reality and start to be commercially available [2]. However, design of composite structures and durability prediction still suffers a lack of confidence over damage evolutions and structural integrity. This is due to their complex behaviour and failure mechanisms which may lead to the use of conservative safety factor values and then significant over design, mass increase and material consumption. In that sense, structural health monitoring (SHM) techniques could fill this gap by assessing damages in these structures in real time, by evaluating the remaining lifetime and integrity [3] and thus allowing design optimisation and mass saving. Acoustic-emission (AE) based SHM is particularly adapted to polymer matrix composites to assess, locate and identify real-time damages and propagation in qualitative and quantitative ways with a limited number of equipment [4]. Embedment of small sensors (millimetre-sized) within the laminate could be an opportunity to get smart materials with enhanced sensitivity while easing the instrumentation and improving the durability of the sensors. Several studies [5–7] have already shown major

advantages in embedding directly sensors within the materials allowing a better coupling between the sensor and the material and providing a packaging around the sensors, thus, limiting the effects of the environment. Moreover, if acoustic emission tends to generate an important amount of data, major breakthrough has been made in the last decades. Nowadays, efficient and reliable signal processing and data mining, through denoising, hits detection and data clustering lead to a fine understanding of the transient acoustic waves induced by damages when composite structures are subjected to loads [8–11]. Sensor technologies and materials have also evolved to improve the signal quality. Among the numerous options, capacitive micromachined ultrasonic transducer (CMUT) technologies are of particular interest. They rely on the use of arrays of small micromachined silicon unit membranes of different resonance frequencies potentially increasing the bandwidth and signal-to-noise ratio of the sensor. Such sensors could be embedded in composite laminates as shown in Figure 1.

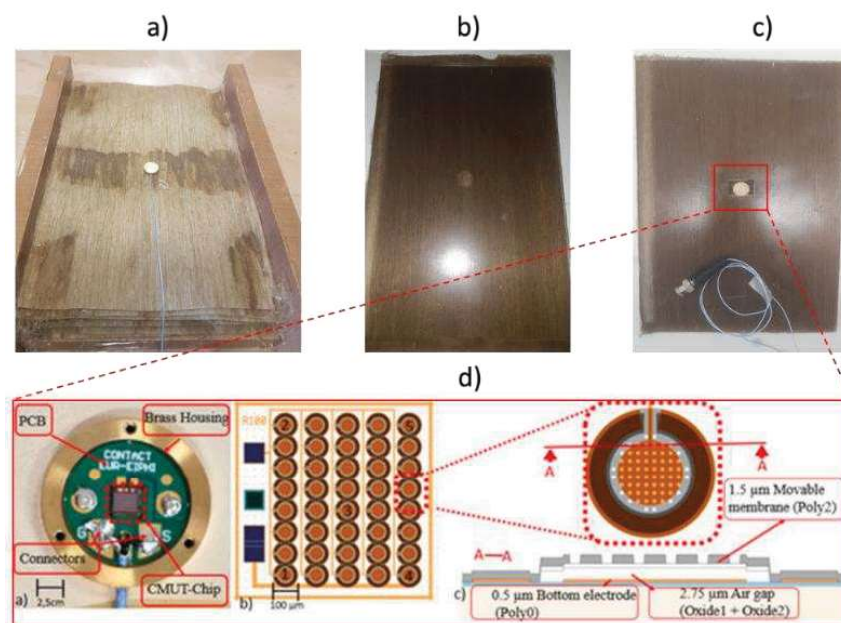


Figure 1 : Embedded CMUTs in a unidirectional flaxtape/GreenPoxy laminate. a) during lay-up; b) after curing, c) after laser cutting to observe the sensor and d) overview of CMUT sensor from [12].

In this work, we propose to study the effect of the embedment of brass parts mimicking CMUT-type AE-sensors on the properties and behaviour of flax-epoxy laminates under monotonic loads conditions as well as on the damage modes and kinetics.

2. Material and methods

Flax/epoxy composites were manufactured by thermocompression. Twenty plies of an unidirectional flax reinforcement (FlaxTape UD110 from Ecotechnilin[®]) were stacked into a Teflon coated steel mould. Epoxy resin (GreenPoxy 56 from Sicomin[®]) was poured between the different layers in the middle of the ply's length all along its width. The mould was then closed except on the length extremities to allow air and matrix excess to flow out. Laminates were then cured in a hot press in two step process: a first impregnation step at 40°C and 3bars for 15min and a curing step at 60°C and 3bars for an hour. Additionally, laminates were post-cured at 130°C.

For embedded insert samples, 10x5x1mm³ brass mimicking sensor parts were dipped into the resin and then placed at the middle ply of the laminate (*Figure 2a*), on the symmetric axis. Samples were laser cut (*Figure 2b*). Few samples were also polished to observe the effect on the microstructure (*Figure 2c*). More details about the process can be found in [13]. Samples were tested under monotonic tensile loads on a MTS Criterion tensile machine at 1mm/min.

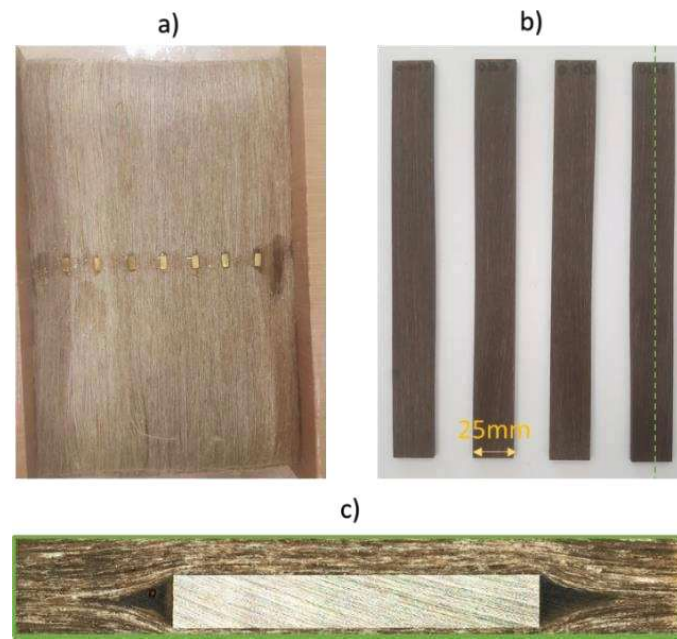


Figure 2 : Dummy sensor embedding a) during manufacturing, b) after laser cut, c) longitudinal microstructural effect of the sensor with matrix rich region in the alignment of the sensor

AE hits were recorded during monotonic tensile tests to evaluate damage modes and kinetics. Each tested specimen was monitored by acoustic emission using two external piezoelectric transducers coupled to the sample. Raw AE data were recorded during the test through a digital picometer and then processed using an algorithm developed in the lab. The raw data were denoised, hits were then identified and matrix of 42 descriptors were extracted. Complete details about AE equipment and processing can be found in [8,13]. Five clusters were then identified using an unsupervised Gustavsson-Kessel algorithm. All combination of 5 parameters were tested and the best set of parameters was retained to plot the representative AE behaviour. The clustering descriptors retained by the algorithm will not be discussed in this paper. This unsupervised clustering method have already been discussed in previous studies [10,11]. X-ray microtomographic images of the broken samples were acquired to enhance AE interpretation, the method details are described in [13].

3. Results and discussions

3.1 Effect of the embedding of dummy sensors on the monotonic properties

Pristine and embedded samples were subjected to monotonic tensile load. The values of the tensile properties are summarised in Table 1. The strain-stress curves are presented in Figure 3. The behaviour of unidirectional laminates is assumed to be bilinear with a first high stiffness ($E_1 = 31 \pm 1$ GPa) step between 0% and 0.15% and a second phase after 0.3-0.4% longitudinal strain where the second apparent modulus is significantly lower ($E_2 = 25.5 \pm 0.5$ GPa). Samples have

brittle failure between 1.2 and 1.5% of longitudinal strain with a stress at break of 340.9 ± 12.9 MPa.

Table 1 : Monotonic tensile properties of pristine and embedded laminates

	Pristine	Embedded	Effect
V_f^1 (%)	49.9 ± 2.8	47 ± 0.5	-
V_p^2 (%)	3.1 ± 0.8	4.5 ± 0.4	-
E_1^3 (GPa)	31.0 ± 1.0	27.7 ± 1.9	-10 %
E_2^4 (GPa)	25.5 ± 0.5	22.7 ± 1.1	-11%
ν_{LT}	0.44 ± 0.02	0.44 ± 0.01	0%
σ_{max} (MPa)	340.9 ± 12.9	276.9 ± 17.0	-19%
ϵ_L (%)	1.32 ± 0.02	1.21 ± 0.01	-8%
ϵ_T (%)	0.51 ± 0.02	0.51 ± 0.02	0%

¹Fibre volume fraction calculated as $V_f = (m_f/\rho_f)/((m_f/\rho_f) + (m_m/\rho_m))$; ² Porosity content $V_p = 1 - \rho_c(w_f/\rho_f + w_m/\rho_m)$; ³First apparent modulus calculated between 0.05% and 0.15%; ⁴Second apparent modulus calculated between 0.4% and break

Interestingly, the presence of a brass part mimicking sensor does not affect the behaviour of the laminates subjected to tensile loads as the bilinear behaviour remains present with a yield point at the same strain level. The two apparent moduli are only slightly decreased (by about 10%) when a dummy sensor is embedded, emphasizing that the presence of sensors would not lead to oversizing materials to obtain comparable structural stiffness. Moreover, ultimate strain is only decreased by 8% when a dummy sensor is embedded. The stress at break appears to be the most affected properties. Indeed, the UTS drop of 19% from 340.9MPa to 276.9MPa when a dummy sensor is inserted. This could be attributed to stress concentration in the matrix rich region located in the insert vicinity. This stress concentration could thus lead to early matrix cracks coalescence, delamination and debonding triggering earlier fibre breaking.

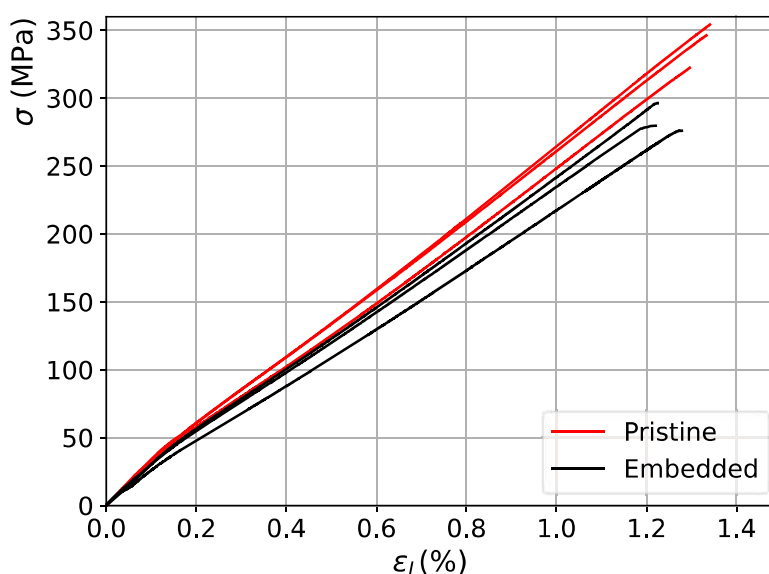


Figure 3 : Monotonic tensile test of pristine and embedded samples

3.2 Effect of sensor embedment on damage modes and kinetics during monotonic tensile testing

Acoustic emission clustering is an useful tool to discriminate damage modes and record damage kinetics during mechanical testing. Traditionally, amplitude, hits number and energy are the preferred AE signal features for clustering, in particular in supervised mono- or multi-parametric methods [14,15] as well as in unsupervised approaches. High energy and amplitude hits are generally correlated to severe damage (such as fibre breaking) that compromise the structural integrity and lead to failure while low energy and amplitude hits are more likely to be related to minor damages (such as matrix cracks) [14–17]. However, even if the utility of AE to discriminate changes in damage modes and kinetics is interesting and clustering methods bring even better insight, one must keep in mind that it is based on a complex unsupervised technique with some unknown about environmental effect and complex behaviour of the waves propagating within the material. Indeed, it has been shown that damages affect the AE signals themselves [9] and this could be even more pronounced when a metallic part is inserted. In that sense, it is preferred in this study to keep an overview of the results to analyse major tendencies without attributing a specific damage mode to a cluster. In addition, X-ray microtomography images of the failed samples, as presented in Figure 4, were analysed to identify the existing damage modes and their location and to ease the understanding and interpretation of changes in AE activity. The evolution of each cluster cumulative hits and energy as function of strain during monotonic tensile testing for both pristine and embedded samples are presented in Figure 5(a) and (b) respectively. Figure 5(c) and (d) represent the amplitude of the hits during the test and Figure 5(e) and (f) represent the energy of the hits during the tests.

For pristine sample, the first three clusters start in the early beginning of the test. For clusters 1 and 2, it is attributed to external sources (such as friction in the clamps) and minor damages (such as microcracking) that occur all along the applied strain. Some early damages and geometrical changes (such as fibres reorientation) of higher amplitude (Cluster 1) also appear in the beginning but slow down after 0.2% strain. At this point, a new cluster (Cluster 4) starts and evolves continuously during the test. This slowing of one cluster while another takes place highlights a change in the damaging behaviour. It is interesting to note that this change occurs simultaneously with the characteristic ill-point of flax composite tensile curves, where the apparent modulus decreases. So, the AE activity in this cluster could be related to nano- and micro-structural changes in the fibre wall. Finally, the fifth cluster starts at much higher strain (0.9%) that can be attributed to much severe damages leading to the final failure. For this cluster, the energy is more important and represents a wide part of the total energy dissipated by the laminate as compared to the other one while the number of hits of this cluster is significantly lower than the other clusters. The clustering result highlights the complexity of the damages occurring in the material, and the chronology of appearing of these damages.

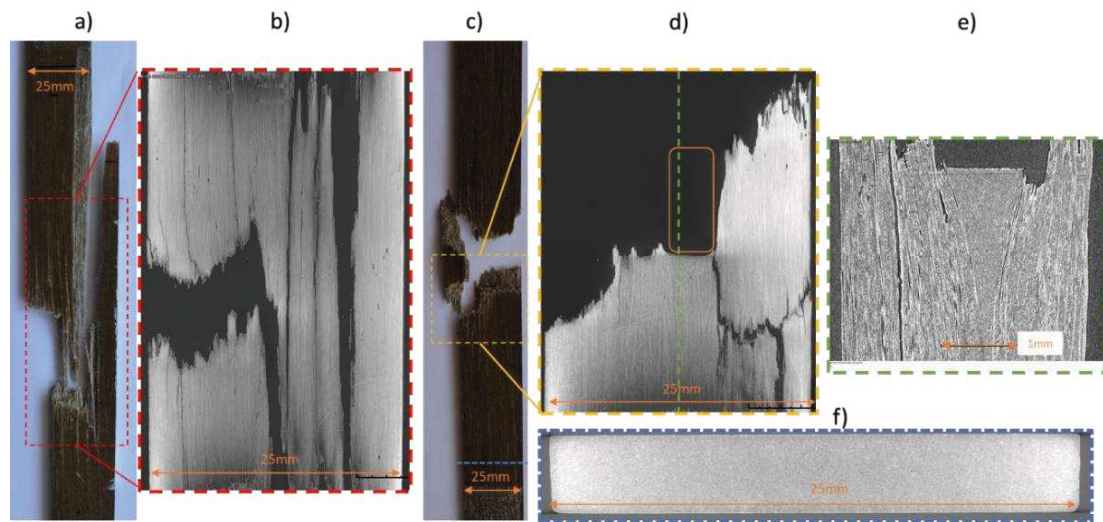


Figure 4 : Failure facies and tomographic observations of the broken a-b) pristine and c-f) embedded samples

Failure facies of pristine sample and tomography reveal long splitting of the laminates and damages in the whole volume. Such observations are coherent with a high number of hits of low energy induced by matrix cracks initiation and propagation in the whole samples. Once the coalescence is important enough, it initiates more energetic breakage of fibres in stress concentrated areas, leading to an energetic brittle fracture.

For embedded samples, it is interesting to note that the overall clusters chronology and trends are comparable to the pristine one with the three early starting clusters. The last two clusters however start at lower strain levels with faster increase in the number of recorded hits than for pristine samples. The number of total hits recorded for embedded samples is slightly lower than for pristine ones while energies are comparable. From these observations, it is important to note that the presence of a brass dummy sensor does not affect damage modes and identified cluster evolution but tends to provoke earlier severe damages leading to a premature failure as highlighted by the lower strain level required to see the last two clusters to start. Interestingly, the cracks in the embedded samples appears to be concentrated in the insert vicinity with failure cracks starting from the matrix rich region. When looking at points far away from the break area, the material seems to be not damaged. Thus, AE and tomography results highlight that the insert concentrate damages in its vicinity conducting to early severe damages thus provoking the failure prematurely. Such observations are in accordance with the observed effect highlighted in Section 3.1 and emphasize the conclusion that the effect of the embedment of dummy sensors affects only moderately the laminates in terms of overall monotonic tensile properties but changes in a more complex way damage initiation and propagation in material. Thus, this subtle effect must be taken with care when sizing structures subjected to more complex loads.

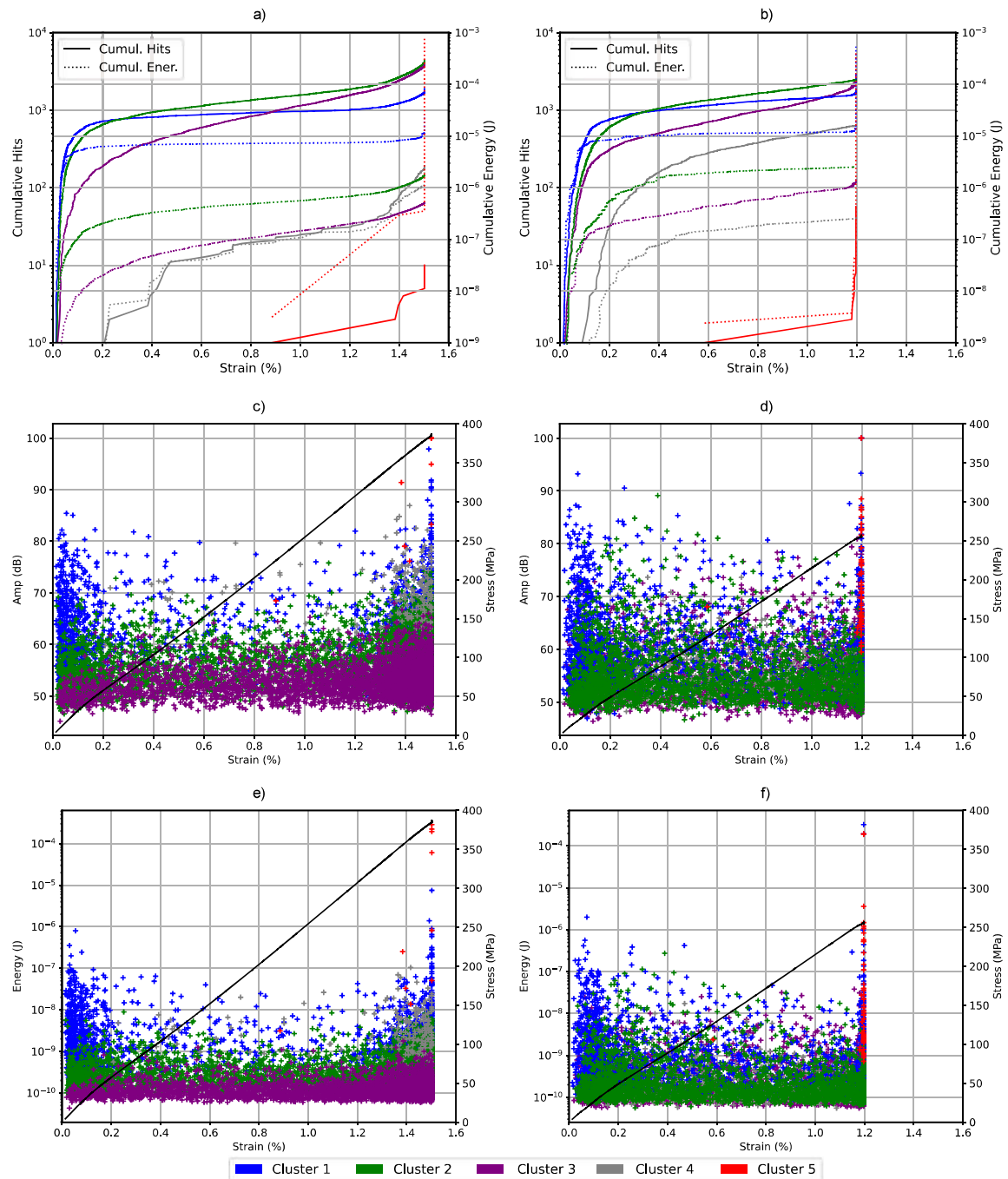


Figure 5 : a) Representative cumulative AE hits and cumulative energy detected per cluster as function of strain for pristine samples and b) embedded samples; c) amplitude of the hits as function of strain for pristine and d) embedded samples; e) energy of the hits as function of strain for pristine and f) embedded samples.

4. Conclusion

Natural Fibres Composites are a promising route to replace glass fibres composite as they showed high mechanical properties. However, their complex behaviour and their properties scattering inherent to their natural origin still limit industrial applications. The use of structural health monitoring such as acoustic emission could thus reduce the unknowns and increase the

reliability of bio-based structures. In this work, we assessed the effect of the embedment of dummy sensors on the integrity of flax/epoxy laminates. Results highlights a limited impact of the integration with no major effect on the overall monotonic tensile behaviour and properties. Regarding damages, the embedment of dummy sensors does not induce the appearance of new damage modes. Only a change in their spatial localisation and their onset times was observed. The presence of a sensor leads to a concentration of damage in its vicinity, leaving the rest of the volume free of damage. It also induces a premature onset of the major damages. However, the global stress at break is only slightly decreased and the effects could be even more reduced by optimising sensor geometry and manufacturing process. So, it can be concluded that in-situ acoustic emission is feasible for bio-based composited and opens opportunities to more sustainable structures.

Acknowledgements

Acknowledgements can be added at the end of the paper, before the references if applicable. This work has been supported by EIPHI Graduate School (contract “ANR-17-EURE-0002”) and the French RENATECH network through its FEMTO-ST technological facility and staff (MIMENTO Clean room). The authors are also grateful to MIFHySTO technological platform (FEMTO-ST, France) for the support in X-ray nanotomography characterisation.

5. References

- [1] Jeannin T, Berges M, Gabrion X, Léger R, Person V, Corn S, et al. Influence of hydrothermal ageing on the fatigue behaviour of a unidirectional flax-epoxy laminate. *Compos Part B Eng* 2019;174:107056. <https://doi.org/10.1016/j.compositesb.2019.107056>.
- [2] Mutel F. Flax and Hemp Fiber Composites, a Market Reality: The Biobased Solutions for the Industry. JEC Group; 2018.
- [3] Mitsheal D. A Review of Structural Health Monitoring Techniques as Applied to Composite Structures 2017:57.
- [4] De Rosa IM, Santulli C, Sarasini F. Acoustic emission for monitoring the mechanical behaviour of natural fibre composites: A literature review. *Compos Part Appl Sci Manuf* 2009;40:1456–69. <https://doi.org/10.1016/j.compositesa.2009.04.030>.
- [5] Masmoudi S, El Mahi A, Turki S. Use of piezoelectric as acoustic emission sensor for in situ monitoring of composite structures. *Compos Part B Eng* 2015;80:307–20. <https://doi.org/10.1016/j.compositesb.2015.06.003>.
- [6] De Rosa IM, Sarasini F. Use of PVDF as acoustic emission sensor for in situ monitoring of mechanical behaviour of glass/epoxy laminates. *Polym Test* 2010;29:749–58. <https://doi.org/10.1016/j.polymertesting.2010.04.006>.
- [7] Tuloup C, Harizi W, Aboura Z, Meyer Y, Khellil K, Lachat R. On the use of in-situ piezoelectric sensors for the manufacturing and structural health monitoring of polymer-matrix composites: A literature review. *Compos Struct* 2019;215:127–49. <https://doi.org/10.1016/j.compstruct.2019.02.046>.
- [8] Kharrat M, Ramasso E, Placet V, Boubakar ML. A signal processing approach for enhanced Acoustic Emission data analysis in high activity systems: Application to organic matrix composites. *Mech Syst Signal Process* 2016;70–71:1038–55. <https://doi.org/10.1016/j.ymssp.2015.08.028>.
- [9] Kharrat M, Placet V, Ramasso E, Boubakar ML. Influence of damage accumulation under fatigue loading on the AE-based health assessment of composite materials: Wave

- distortion and AE-features evolution as a function of damage level. *Compos Part Appl Sci Manuf* 2018;109:615–27. <https://doi.org/10.1016/j.compositesa.2016.03.020>.
- [10] Ramasso E, Butaud P, Jeannin T, Sarasini F, Placet V, Godin N, et al. Learning the representation of raw acoustic emission signals by direct generative modelling and its use in chronology-based clusters identification. *Eng Appl Artif Intell* 2020;90:103478. <https://doi.org/10.1016/j.engappai.2020.103478>.
- [11] Ramasso E, Placet V, Boubakar ML. Unsupervised Consensus Clustering of Acoustic Emission Time-Series for Robust Damage Sequence Estimation in Composites. *IEEE Trans Instrum Meas* 2015;64:3297–307. <https://doi.org/10.1109/TIM.2015.2450354>.
- [12] Boubenia R, Le Moal P, Bourbon G, Ramasso E, Joseph E. CMUT-Based Sensor for Acoustic Emission Application: Experimental and Theoretical Contributions to Sensitivity Optimization. *Sensors* 2021;21:2042. <https://doi.org/10.3390/s21062042>.
- [13] Seychal G, Ramasso E, Le Moal P, Bourbon G, Gabrion X, Placet V. Towards in-situ acoustic emission-based health monitoring in bio-based composites structures: Does embedment of sensors affect the mechanical behaviour of flax/epoxy laminates? *Compos Part B Eng* 2022:109787. <https://doi.org/10.1016/j.compositesb.2022.109787>.
- [14] Godin N, Reynaud P, Fantozzi G. Émission acoustique et durabilité des composites. 2018.
- [15] Marec A. Damage characterization of polymer-based composite materials: Multivariable analysis and wavelet transform for clustering acoustic emission data. *Mech Syst Signal Process* 2008:24.
- [16] Monti A, El Mahi A, Jendli Z, Guillaumat L. Mechanical behaviour and damage mechanisms analysis of a flax-fibre reinforced composite by acoustic emission. *Compos Part Appl Sci Manuf* 2016;90:100–10. <https://doi.org/10.1016/j.compositesa.2016.07.002>.
- [17] Munoz V, Valès B, Perrin M, Pastor ML, Weleman H, Cantarel A, et al. Damage detection in CFRP by coupling acoustic emission and infrared thermography. *Compos Part B Eng* 2016;85:68–75. <https://doi.org/10.1016/j.compositesb.2015.09.011>.