Monitoring Damage Evolution in Carbon/ Epoxy and Carbon/Thermoplastic Composites using Acoustic Emission Technique

MANOJ RIJAL, TRAVIS OBIE-ROLLE
and MANNUR SUNDARESAN

ABSTRACT

Detecting, monitoring, and quantifying the growth of damage in structural components in real time is important for assuring safety of aerospace structures. Acoustic emission (AE) technique is one of the tools that can facilitate such monitoring and quantification of damage growth and provide meaningful insight into damage evolution. Damage growth in composite materials has long been studied under laboratory setting and documented in the literature, but there is a need to track such failure modes in real structures under operational conditions. In this study the progression of damage in pristine carbon/epoxy composites under static loading were examined. Bonded wide band sensors capable of detecting frequency components up to 2 MHz were used to differentiate signals from the three primary AE sources, namely, matrix cracks, delaminations, and fiber breaks. Traditional acoustic emission parameters as well as the waveform characteristics were used to classify the acoustic emission signals related to the three failure modes. Individual clusters of fiber breaks, progressive growth of individual matrix cracks as well as delamination growths were also traced using these techniques. The correspondence between the failure mode and the respective waveforms characteristics were validated to a limited extent using both experimental techniques as well as numerical simulations. Based on these classifications, the rate of growth of individual failure modes was also quantified using their respective cumulative energy. The appearance of greater number of AE clusters related to fiber breaks and the increase in their sizes along with cumulative energy are found to be a clear indication of impending failure.

INTRODUCTION

With significant increase in the use of carbon fiber reinforced polymers (CFRP) in various structures, effective monitoring of CFRP composites has been crucial aspect in ensuring integrity and safety in these structures. Acoustic emission (AE) provides such means of real-time structural health monitoring of CFRP structure and material

Manoj Rijal, Travis Obie-Rolle, Mannur Sundaresan, North Carolina A&T State University, 1601 East Market Street, Greensboro, N.C., 27411

systems. Acoustic emissions are defined as transient stress waves generated by the rapid release of energy from localized sources. In the case of composite structures, the sources and nature of acoustic emission signals are greatly influenced by interaction of composite sub-systems (fiber and matrix) and the nature of loading subjected to the structure [1]. Primary AE sources found in composite material include matrix-cracks, delaminations, and fiber breaks. Composite members undergo extensive damage in the form of these failure modes throughout their quasistatic loading cycle as well as under fatigue before the catastrophic failure is precipitated. An important factor in analyzing these results is the consideration of frequency and mode dependent attenuation experienced by AE signals as they travel to the nearby sensors [2]. Appropriate quantification of AE signals relating to these failure modes is also crucial in assessing the total damage and damage evolution in the structure. The objective is to estimate the margin available before such an event.

Several characterization methods of AE signals for different failure modes have been developed by researchers in the past. Classification based on single AE signal parameter (amplitude, frequency), classification based on several parameters using pattern recognition and classification based on extensional and flexural mode content (modal acoustic emission) are three main approaches used to characterize AE signals [3] .Classification based on amplitude had been long studied but fails to provide reliable demarcation of failure modes as seen from the inconsistencies in these studies[4], [5].Similarly, classification based on peak frequency content has been able to provide some level of consistency [3], [6] but are seen to be limited by the frequency bandwidth of AE sensors used in experiments. Various supervised and unsupervised machine learning algorithms [7] are also being used in classifying AE sources using waveform features but this approach is seen to be limited as AE features calculated are highly influenced by acquisition parameters and may not provide reliable information on that related individual waveforms to the underlying failure events. Modal acoustic emission analysis [8] appears to provide efficient means of classification. Furthermore, cross correlation technique is also established to be an efficient tool in extracting localized damage growth and monitor development of such damages in terms of cluster number and sizes [9]–[12].

In this study, only the occurrence and evolution of delamination, matrix-crack and fiber-break events under quasi-static loading are examined. Classification based on modal acoustic emission is applied in conjunction with pattern recognition technique. In the first part of the study, AE signals are collected during quasi-static tensile test of cross-ply thermoset composites. The nature of waveforms for considered failure modes are also estimated by using wave propagation in finite element analysis. Based on the results from FEM, the waveforms from experiments are then labelled using visual inspection to create substantial waveforms for each failure mode. In the second part, cross-correlation is then used to establish clusters of similar signals indicative of similar failure mode and location. The formation of clusters of individual failure modes and their evolution are analyzed and quantified using cumulative energy in an attempt to quantify the level of damage in the specimen and to predict impending tensile failure of the specimen.

EXPERIMENTAL ANALYSIS

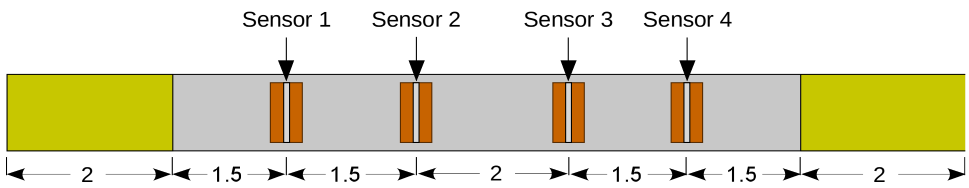


Figure 1. Schematic for specimen and location of bonded sensors

Several specimens of cross ply carbon fiber thermoset composite with layup sequence of $[0/90]_{6s}$ and thickness of 0.075" were loaded under quasi-static tension until failure. Each specimen was bonded with four PZT wafers with frequency response up to 2 MHz and glass-epoxy tabs at the end for gripping as seen in Figure 1. AE signals were recorded using sampling frequency of 40 MSPS. The signals from the transducers were amplified by 60 dB using commercial preamplifiers with 50 kHz high pass filters. A threshold of 40 dB was set for acquiring the AE signals. The AE signals were also filtered using bandpass analog filters with bandwidth of 50 kHz – 3 MHz. Representative results obtained by a pair of adjacent sensors with a spacing of 1.5 inches are presented here.

NUMERICAL ANALYSIS

Routine finite element analysis was used to generate waveforms corresponding to the individual failure modes in terms of Lamb waves modes expected. Only the zeroth order mode shapes were considered for this study. Summary of expected Lamb wave modes and corresponding failure are stated in Table I. Depending on the location of the event matrix-crack and fiber break are expected to have only S_0 mode if the failure event occurred close to the neutral axis and a combination of S_0 and A_0 with different amplitude ratios if the failure events occurred away from the neutral axis. Similarly, delamination is expected to have only flexural mode based on the nature of failure.

Table I. FAILURE MODES AND EXPECTED LAMB WAVES MODES.

Failure modes	Lamb wave modes
Delamination	A_0
Matrix-Crack	S_0 or (S_0+A_0)
Fiber-Break	S_0 or (S_0+A_0)

Table II. MECHANICAL PROPERTIES OF CFRP LAMINA

E_1 (psi)	$E_2 = E_3$ (psi)	$\mu_{21} = \mu_{31}$	μ_{32}	$G_{12} = G_{13}$ (psi)	G_{23} (psi)	ρ $(lbfs^2/in^4)$
2.03e7	1.45e6	0.0225	0.4782	8.26e5	5.22e5	1.46e-4

Several 2D models with dimensions 12” x 0.075” and element size of 0.004” and material properties as indicated in Table II were analyzed using FEM to extract representative waveforms for various failure modes. From the FEM analysis, modal response of failures modes as described in Table I is seen to hold true with matrix-crack having frequencies from 200-500 kHz and fiber-breaks having frequency up to 2000 kHz with delaminations having low frequencies below 150 kHz.

RESULTS AND DISCUSSION

Based on the expected waveforms of failure modes obtained from FEM, signals obtained during experiments were labeled into respective failure modes by visual inspection to generate reasonable reference waveforms. The entire signals were then correlated with reference waveforms to generate clusters of similar failure modes.

Cross-Correlation

Cross-correlation gives the measure of similarity between two signals representing similar location and event in the present study. The size of correlation window and minimum correlation coefficient considered is seen to highly influence formation of clusters. A suitable correlation window and minimum correlation coefficient is hence established using duration of signals in each failure mode as seen in Table III.

It is assumed that closely resembling waveforms are generated by failure events that are related to growth of an individual matrix crack or delamination event or ones that are located very close to each other. Clusters of delamination related waveforms had only a few members while clusters of waveforms related to matrix cracks appear to have a few tens of members. Numerous clusters of fiber break related waveforms with over a hundred members were seen. Representative examples of clusters of waveforms are shown in Figure 2. Clusters of fiber-break were also seen to increase both in numbers and members as specimen approached failure.

Table III. CORRELATION WINDOW AND COEFFICIENT CONSIDERED FOR CLUSTERING THE SIGNALS.

Failure mode	Correlation Window	Min Correlation
Delamination	75 µsec	0.85
Matrix-Crack	45 µsec	0.9
Fiber-Break	15 µsec	0.95

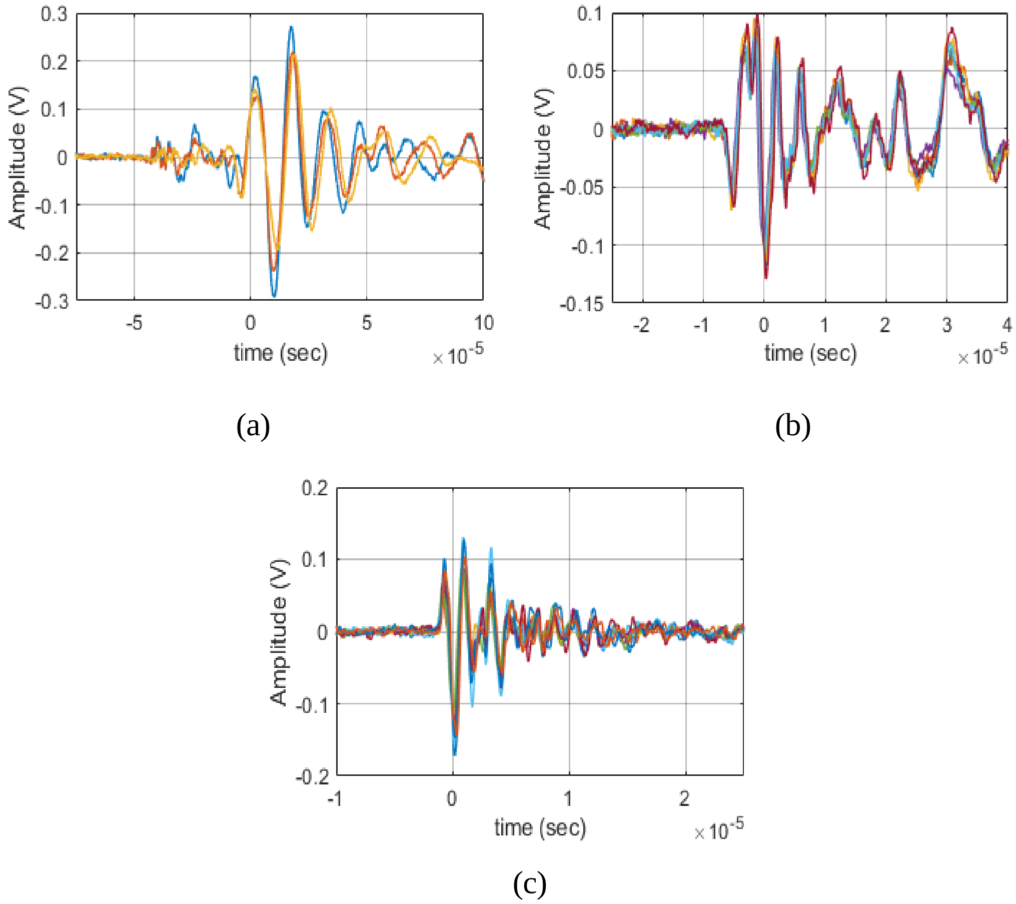
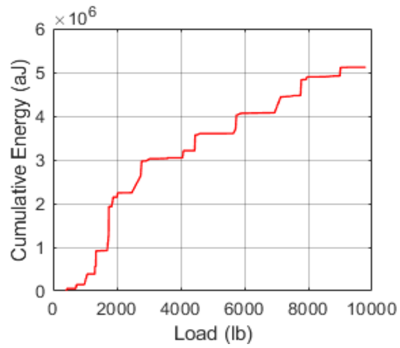


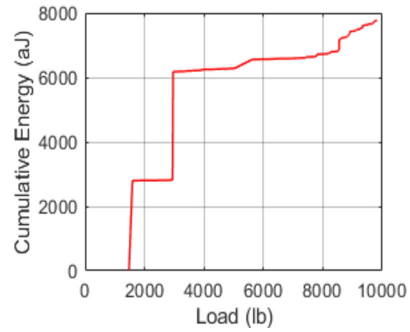
Figure 2. Superimposed signals in clusters belonging to (a) delamination (b) Matrix crack (c) Fiber break

Cumulative AE energy

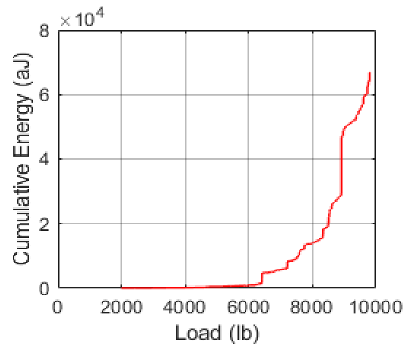
Each cluster obtained by cross-correlation was also quantified by calculating AE energy of corresponding correlated waveform. Figure 3 shows the evolution of cumulative energy in cluster obtained for delamination, matrix-crack, and fiber-break respectively. The discrepancies in shape of the cumulative energy plot can be attributed to all waveforms not being classified indicating the need of rigorous classification models or extensively labelled datasets to use cross-correlation. Deflection in cumulative energy plot also gives the indication of onset of each failure modes. A significant increase in cumulative energy in fiber-break cluster is also observed as the specimen approached failure as seen in Figure 3(c). Figure 4 shows the AE energy of individual fiber-break clusters observed above 80% of load level which indicates that cluster energy also increases as the specimen approaches failure. Similar trend in cumulative energy of clusters of fiber-break above 80% of ultimate load can also be observed as seen in Figure 5.



(a)



(b)



(c)

Figure 3. Evolution of cumulative energy for (a) Delamination (b) Matrix-crack (c) Fiber-break

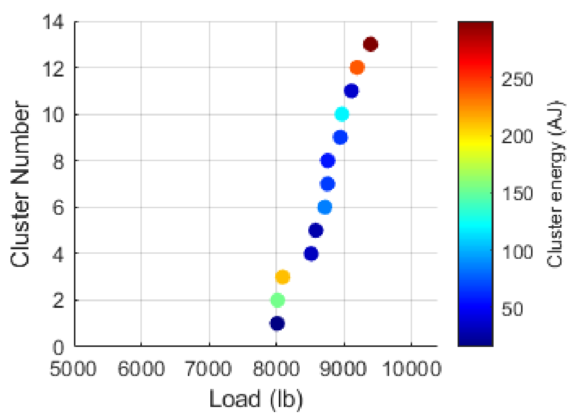


Figure 4. Cluster energy for fiber-break signals occurring above 80% of load level.

Figure 6-7 show the representative waveform and its wavelet diagram for delamination, matrix-crack, and fiber-break respectively. From the wavelet diagram, it can be clearly observed that frequency contents in individual failure modes match the frequency content as stated in numerical analysis section.

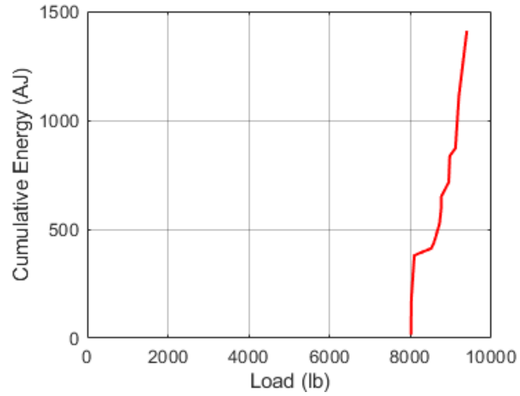


Figure 5. Cumulative energy of clusters of fiber-break above 80% of ultimate load.

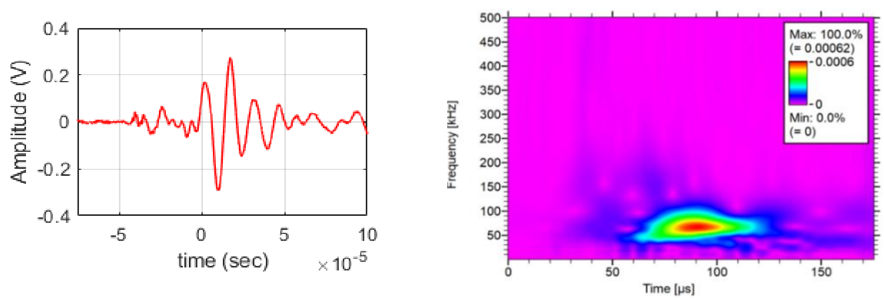


Figure 6. Representative waveform for delamination and its wavelet

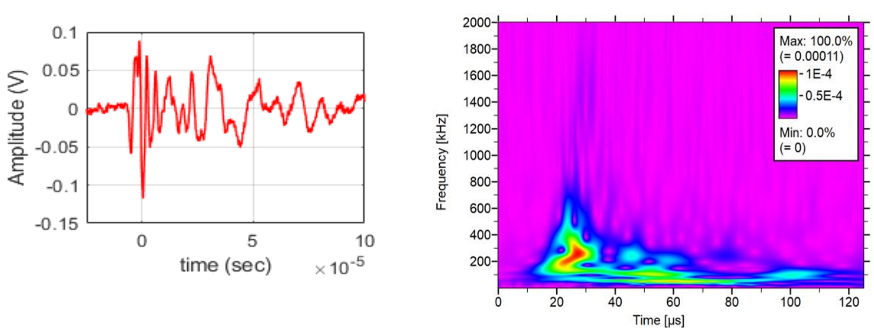


Figure 7. Representative waveform for matrix-crack and its wavelet.

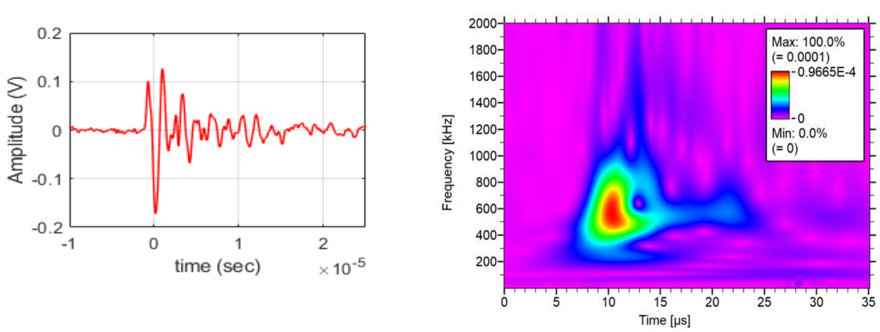


Figure 8. Representative waveform for fiber-break and its wavelet.

CONCLUSION

Acoustic emission signals obtained during quasi-static tensile test of carbon fiber composites were analyzed and classified using expected event durations and information from finite element simulations. Cross-correlation was used to group events in each category originating from adjacent locations. In addition, the waveforms were visually examined to provide examples for automated classification. Cumulative energy corresponding to the three failure modes is used to provide an indication of the accumulated damage before the final failure. For specimens loaded in tension, energy corresponding to the individual as well as clusters of fiber breaks appears to be the most accurate predictor of the impending failure.

REFERENCES

[1] C. Barile, C. Casavola, G. Pappalettera, and V. P. Kannan, "Application of different acoustic emission descriptors in damage assessment of fiber reinforced plastics: A comprehensive review," *Engineering Fracture Mechanics*, vol. 235. Elsevier Ltd, Aug. 01, 2020, doi: 10.1016/j.engfracmech.2020.107083.

[2] K. Asamene, L. Hudson, and M. Sundaresan, "Influence of attenuation on acoustic emission signals in carbon fiber reinforced polymer panels," *Ultrasonics*, vol. 59, pp. 86–93, 2015, doi: 10.1016/j.ultras.2015.01.016.

[3] R. Gutkin, C. J. Green, S. Vangrattanachai, S. T. Pinho, P. Robinson, and P. T. Curtis, "On acoustic emission for failure investigation in CFRP: Pattern recognition and peak frequency analyses," *Mech. Syst. Signal Process.*, vol. 25, no. 4, pp. 1393–1407, May 2011, doi: 10.1016/j.ymssp.2010.11.014.

[4] J. M. Berthelot and J. Rhazi, "Acoustic Emission in Carbon Fibre Composites," 1990.

[5] D. Valentin, P. Bonniau, and A. R. Bunsell, "Failure mechanism discrimination in carbon fibre-reinforced epoxy composites," *Composites*, vol. 14, no. 4, pp. 345–351, 1983, doi: https://doi.org/10.1016/0010-4361(83)90153-2.

[6] P. J. De Groot, P. A. M. Wijnen, and R. B. F. Janssen, "REAL-TIME FREQUENCY DETERMINATION OF ACOUSTIC EMISSION FOR DIFFERENT FRACTURE MECHANISMS IN CARBON/EPOXY COMPOSITES," 1995.

[7] N. Godin, S. Huguet, R. Gaertner, and L. Salmon, "Clustering of acoustic emission signals collected during tensile tests on unidirectional glass/polyester composite using supervised and unsupervised classifiers," *NDT E Int.*, vol. 37, no. 4, pp. 253–264, Jun. 2004, doi: 10.1016/j.ndteint.2003.09.010.

[8] M. Surgeon and M. Wevers, "Modal analysis of acoustic emission signals from CFRP laminates," *NDT&E Int.*, pp. 311–322, 1999, [Online]. Available: www.elsevier.com/locate/ndteint.

[9] T. Whitlow and M. Sundaresan, "Clustering of Fiber-Break Related Events in Carbon Fiber Reinforced Polymer Composites Using Acoustic Emission," 2017. [Online]. Available: http://www.ndt.net/?id=21552.

[10] B. Mills-Dadson, K. ASAMENE, T. Whitlow, and M. Sundaresan, "Acoustic Emissions from Damage Mechanisms in Composites," 2015, doi: 10.12783/SHM2015/189.

[11] D. Q. Tran and M. Sundaresan, "Acoustic emission monitoring of rate of damage growth in composite structures (Conference Presentation)," in *Smart Structures and NDE for Energy Systems and Industry 4.0*, 2019, vol. 10973, p. 109730L, doi: 10.1117/12.2518273.

[12] D. Rajendra, T. Knighton, A. Esterline, and M. J. Sundaresan, "Physics-based classification of acoustic emission waveforms," in *Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2011*, 2011, vol. 7983, p. 79833H, doi: 10.1117/12.880668.