# Advanced Acoustic Emission Monitoring of Sub-Zero Temperature Dynamic Loading of Marine Composite Materials

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Abstract

*In this paper we give a brief on experimental and analytical work on the use of acoustic emission (AE) in following the progressing damage as marine composite sandwich samples are loaded in fatigue, and for comparison, in static bending, at room and sub-zero temperatures. It has been observed that AE is the best tool for monitoring the dynamics of internal damage [1-4] and that AE signals convey an abundance of useful information, including those that highlight the modes that carry significant energy as well as the frequency bands where such notable energy levels occur in such modes [5], thus making AE an ideal tool for source location of singularity events. Significant AE amplitude changes have also been concluded to occur for relatively small frequency changes thereby underscoring frequency analysis techniques as being very efficacious for processing AE signals [6]. One of the presently most advanced signal processing methods is the wavelet transform method, which essentially combines measures of time with some representations of frequency and intensity. In this work, AE data was synchronously acquired as the mechanical test progressed. Normal parametric analysis, general joint time-frequency and especially wavelet transform techniques were applied to the AE test data obtained from wide-band sensors. Analyses of trend records and spot-records at particular time instants gave both qualitative and quantitative depictions of failure modes, their sequences and interactions*

## 1. Introduction

Ocean-going vessels many times need to work in low temperature waters.The behavior of ship hull materials in such environments must therefore be understood. This need drives more thorough investigation of low temperature responses of marine composites. The present paper informs about some experimental and analytical work on the use of acoustic emission (AE) in following the progressing damage as marine composite sandwich samples are loaded in fatigue, and for comparison, in static bending, at room and sub-zero temperatures. It has been observed that AE has been recognized as perhaps the best tool for monitoring the dynamics of internal damage [1-4] identified to carry a plethora of useful information, especially those that emphasize the modes conveying significant energy and also the frequency bands where those significant energy levels are found [5], thereby establishing AE a most appropriate means to locate singularity events. It has also been noted Sthat quite high AE amplitude changes tend to occur for relatively small frequency changes thus authenticating frequency analysis techniques as rather highly efficient for AE signals processing [6]. Surgeon and Weaver [7] explored in detail the use of the modal acoustic emission approach for diagnostics and classification of structural damage, concluding that the use of wave frequency and extensional to fracture wave amplitudes gives results superior to traditional AE analysis. Kotsikos et al. [8] found cumulative AE events and count rate strongly indicative of damage accumulation. Qi [9] extolled the utility of energy distribution of wavelet-decomposed AE signals in diagnosing and characterizing damage. Dzenis and Saunders [10] used a commercial statistical AE pattern digital classification software (VisualClass, Vallen AG) for mixed-mode fatigue failures of adhesive composite joints, and prognosticated wider use of this approach for predictive fracture and remaining useful life modeling. Johnson [11] proposed an AE classification scheme based on Partial Least Squares Regression with numerically simulated AE-signals. Choi et al. [12] demonstrated that FFT transforms of AE signals and event distributions proved sufficient to classify the failures in the cryogenic cooling of composites. Steel et al. [13] postulated correlations between event rate and crack length can be used as a diagnostic tool for modeling composite fatigue damage. Ramirez-Jimenez et al. [14] demonstrated the existence of a relationship between composite micromechanical failure events and specific frequencies. Silva et al. [15] showed that various indices from fractal analysis can distinguish between different composite failure mechanisms. Quispitupa et al. [16] used amplitude, energy and events density distributions to diagnose and classify damage in the tensile loading of sandwich composites. Leone, Caprino and Iorio [17] used cumulative AE events with artificial neural networks to predict the residual strength of FRPs, and conclude that the results were reliable. Bourchak et al. [18] also concluded from their work that AE energy has proved to be a reliable indicator of CFRP composites.

The wavelet transform method is presently considered one of the most advanced signal processing methods. It basically combines measures of time with those of frequency and intensity. In the work reported here, AE data was acquired on a time-lock basis with the mechanical test. Parametric analysis and wavelet transform techniques were applied to the AE test data obtained from wide-band sensors. Qualitative and quantitative depictions of failure modes, their sequences and interactions were employed in analyses of trend records and spot-records at particular time instants.

## 2. Experimental work

Concurrent and synchronized AE data acquisition with miniature PAC pico-AE sensors was carried out while static 4-point bending tests were performed on the composite sandwich (CS) beams with Rohacell (PMI) foam core and unidirectional carbon/epoxy skin material at 22 $^0$C, 0 $^0$C, -30 $^0$C and at -60 $^0$C respectively inside an environmental chamber of an EnduraTec servo-pneumatic testing machine. 4-point fatigue bending tests in accordance with ASTM C393-62 were also performed with the same apparatus at 2 Hz frequency and 0.1 loading ratio (min. load/max. load per cycle) to simulate sea wave effects at the different temperatures of RT, 0 $^0$C and -60 $^0$C with load levels, and in the range from 70 to 90 percent of static ultimate load. Crack propagation was tracked with a digital camera in the fatigue tests. AE data was processed with a Physical Acoustics AE-Win system.

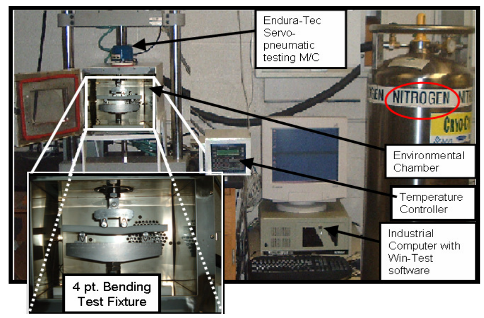


Fig. 1. Experimental Setup

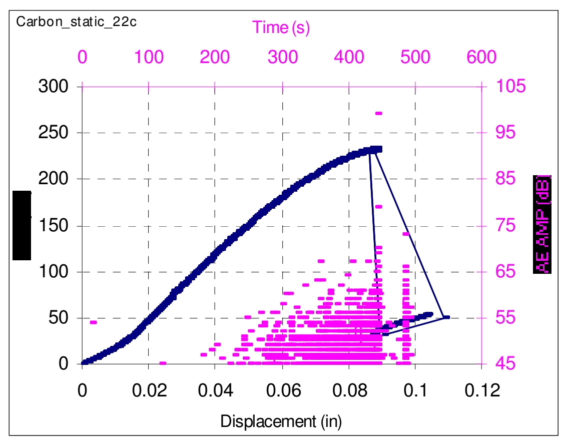


Fig. 2. Typical Load-Displacement curve with superposed AE amplitudes (RT GF/RC)

## 3. Results and Discussion

### 3.1 Fidelity of AE to mechanical tests

Figure 2 shows a typical load-displacement curve, here for the glass fiber/rohacell core GF/RC sandwich. Other results show that stiffness, strength and elastic limit are enhanced by cooling and displacement to failure is lowered.

Figure 3 similarly shows a typical displacement-cycles plot, here for the carbon fiber/rohacell core sandwich at room temperature. AE activity is observed from the start of loading, and climaxes rather sharply at breakage. AE records were found to be very faithful to the mechanical test results in all cases. Figure 4 shows this faithfulness in a comprehensive manner across materials and temperatures used in the tests.

Rather little stiffness reduction was observed at -60 $^0$C, greatly enhancing useful fatigue life, unlike at RT that showed notable reductions quite early.

In general, the catastrophic failures occurred too rapidly for the high-speed camera. However, the utility of the AE approach is demonstrated in the way in which it captured pretty much everything that happened, an event-by-event record of the damage progression and ultimate failure.

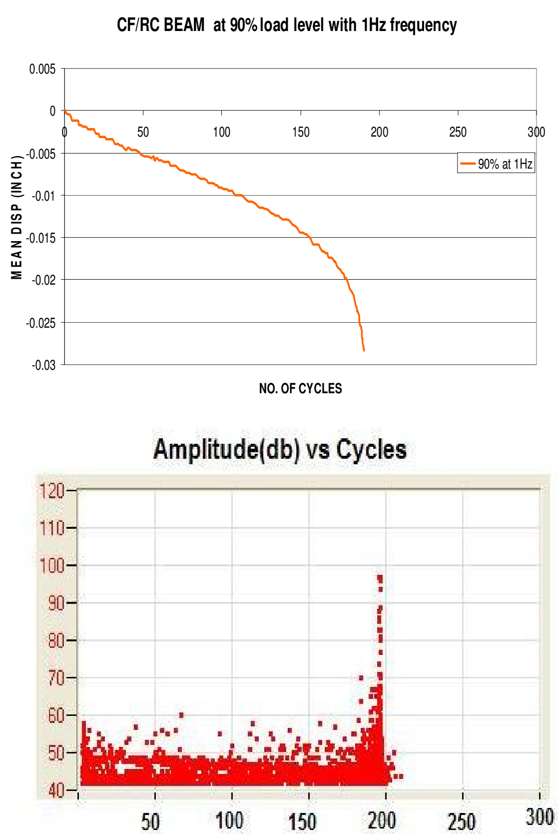


Fig. 3. Typical Disp-Cycles curve with attached AE amplitudes (RT CF/RC)

**3.2** AE synchrony of events


Fig. 5. Amplitude (dBAE), Energy (μJ), and RMS (V) vs Time for GF/RC at -60°C

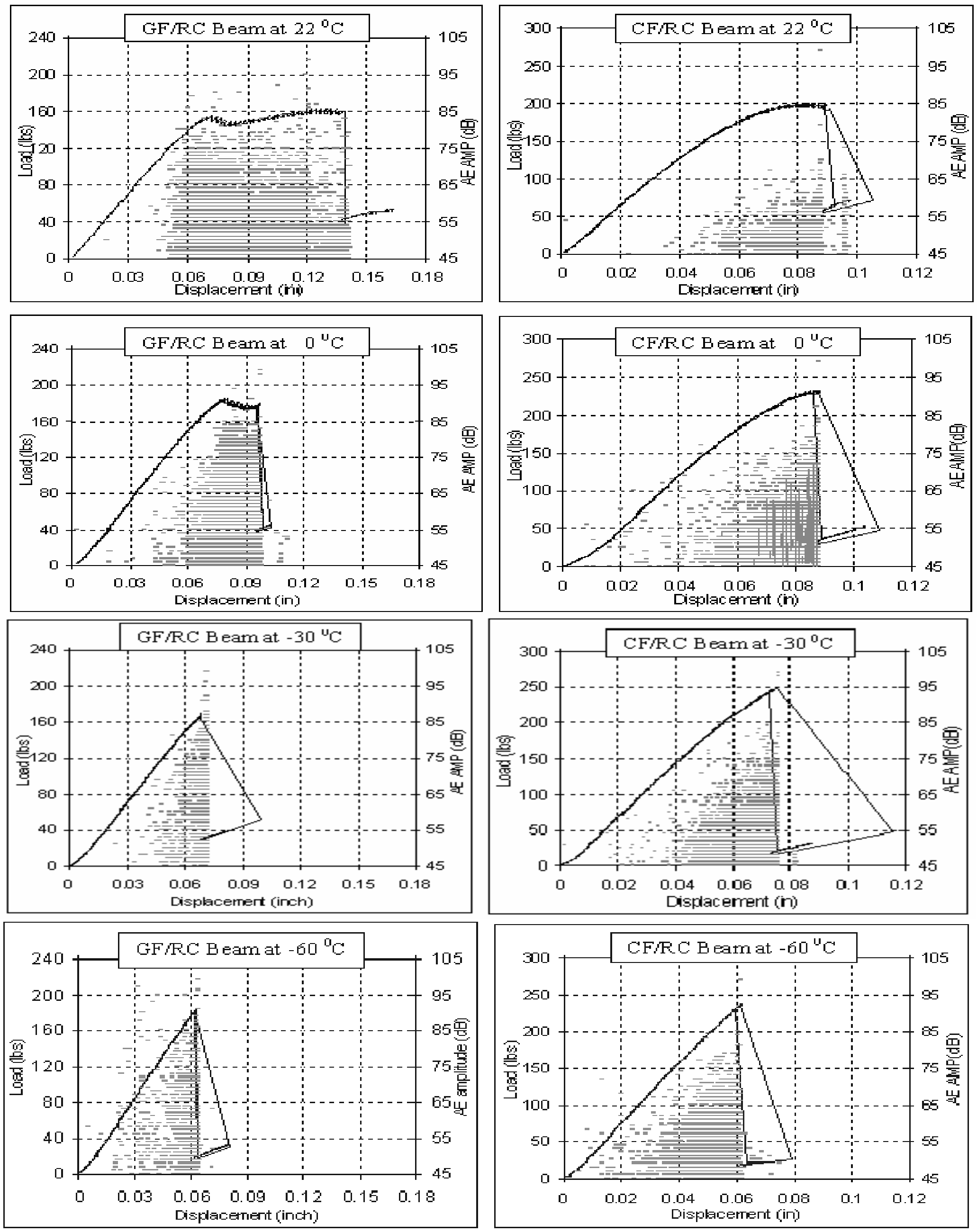


Fig. 4.Load (lb) vs Displacement (m) curves with superposed AE amplitudes (dBAE) vs Time (sec) curves for GF/RC (left) and CF/RC (right) for temperatutes RT 22degC (top), 0 degC, -30 degC, and -60 degC (bottom).

Fig. 5 shows that various AE parametric data give similar heuristic presentations which chronicle damage progression in the tested samples. The failure zone is clearly shown on the different parametric charts, and the synchrony is apparent. The terminal catastrophic failure damage events are by far the most energetic and largest in amplitude, although, amplitude-wise, high value events seem to occur almost throughout the test regimen.

### 3.3 Failure characterization

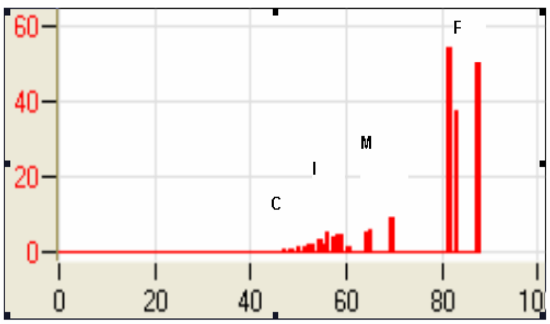


Fig. 6. Energy (µJ) vs Amplitude (dBAE) for GF/RC at -60°C

C = core failure, I = interfacial failures, M = matrix cracking,

F = fiber failure.

As an example, in Fig. 6 may be seen the variation of Energy with Amplitude for the glass fiber/ rohacell sample at the lowest test temperature. The stratification into events types is visible, when discriminated on the basis of AE energy, as in the literature [16, 18]. We may conclude for the zones shown identifiable failure events include the very low energy core failure events, the slightly higher energy interfacial failure events, the moderate energy matrix damage events and the high-energy fiber failures.

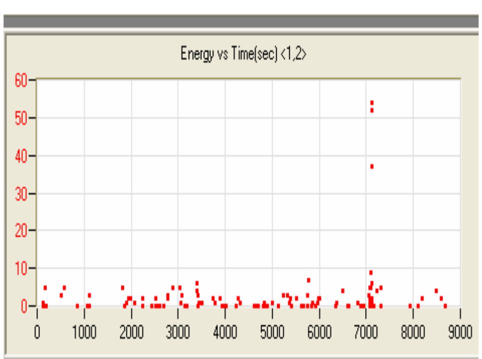


Fig. 7a.Energy (µJ) vs. Time (sec) for GF/RC at -60degC

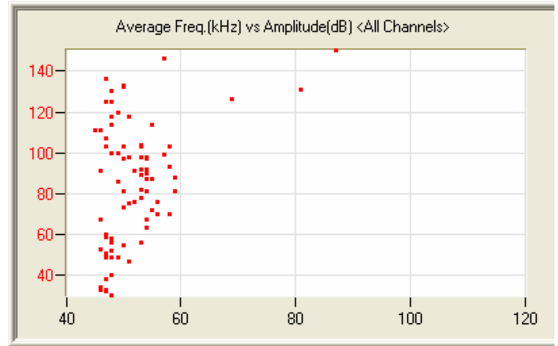


Fig. 7b.Freq (kHz) vs. Amplitude (dBAE) for GF/RC at -60degC

### 3.4 Data filtration

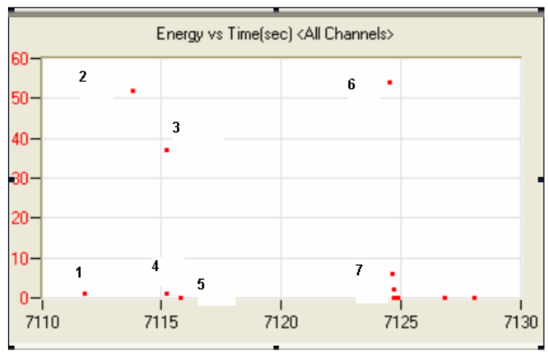


Fig. 8a.Energy (µJ) vs. Time (sec) for GF/RC at -60degC

[Points denote individual damage events]

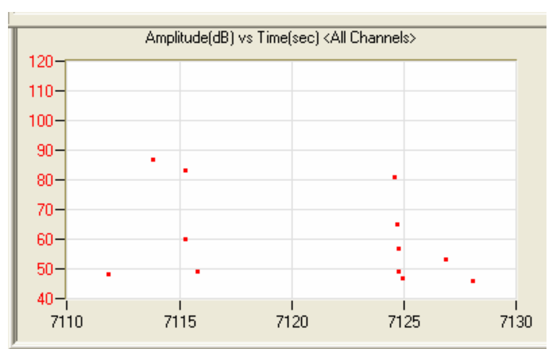


Fig. 8b.Amplitude (dBAE) vs. Time (sec) for GF/RC at -60degC

Figures 8a and 8b show filtered data with the window set around the catastrophic failure zone. It may be seen that AE events 2, 3 and 6 are the most energetic damage events in this zone. For possible transient analysis, each event has a waveform which may be transformed by the Fourier or Wavelet approaches.

3.5 Wavelet Analysis

Figures 9 and 10 show waveforms and 2-D and 3-D wavelet transform plots of typical breaking events. AE wavelet greatly clarifies damage progress. Quite a lot of inferences can be made from the waveform and wavelet transforms. Modal AE principles may be applied to the waveform to determine arrival times and relative maxmum amplitudes of the extensional and flexural waves in each case to determine which is dominant,, and what failure type may have given rise to it. The time of occurrence and the frequency and intensity magnitudes may also be compared for these transforms, further clarifying the failure classification exercise.

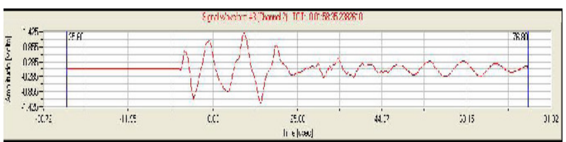

Fig. 9a.Waveform for #3 event of GF/RC at -60degC

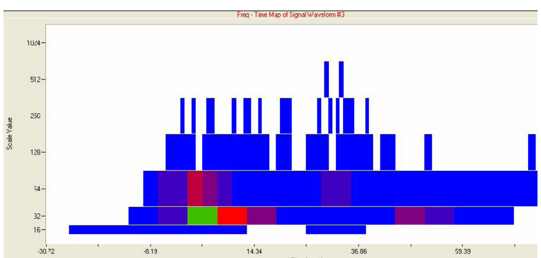

Fig. 9b. 2D-Wavelet for #3 event of GF/RC at -60degC

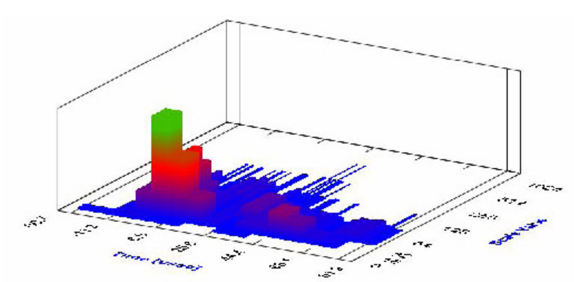

Fig. 9c. 3D-Wavelet for #3 event of GF/RC at -60degC

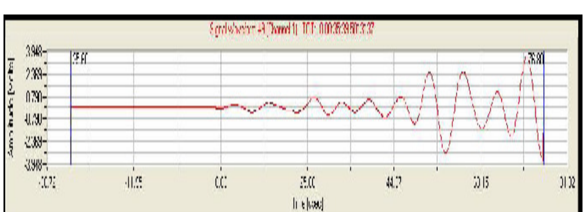

Fig. 10a. Wavelform for #9 event of CF/RC at -60degC

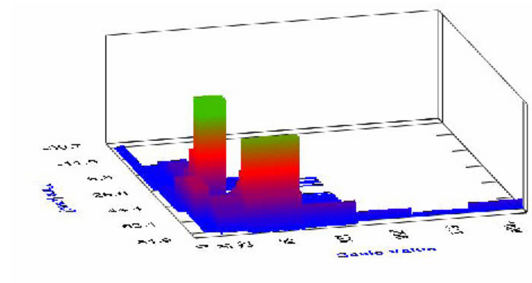

Fig. 10b. 3D-Wavelet for #9 event of CF/RC at -60degC

3.6 Comparisons

The mechanical versus AE record comparison can be inferred from the Figures 2, 3 and 4. Comparison of the GF/RC and CF/RC responses shows that the glass samples take longer (about 4 to 5 times longer) to finally fail than the carbon samples. The carbon samples show more intense AE activities than the glass, as Figure 11 illustrates, perhaps reflecting their relatively higher brittleness.

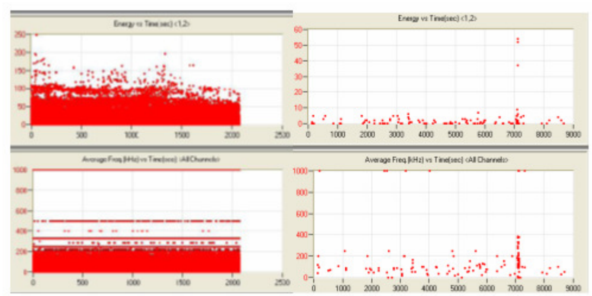

Fig. 11 Characteristic Energy (μJ) vs, Time (sec), top and Freq (kHz) vs Time (sec), bottom, responses of CF/RC (left) and GF/RC (right).

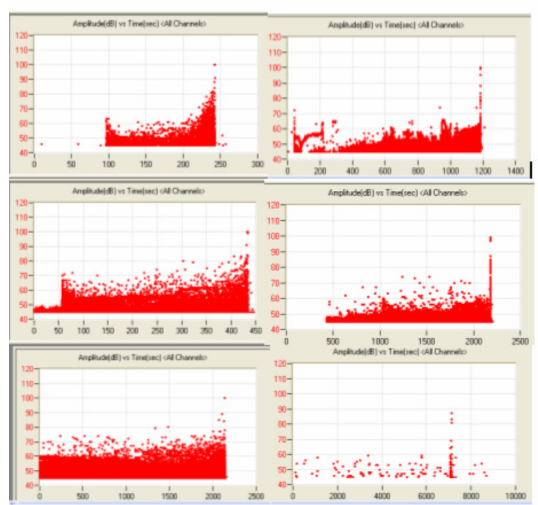

Fig. 12 Characteristic Amplitude (dBAE) vs, Time (sec), plots for RT, 22degC (top), -30 degC (middle), and -60 degC (bottom), for CF/RC (left) and GF/RC (right)

Figure 12 confirms that the lower the temperature, the longer the sample takes to fail in fracture. The pattern of most energetic terminal failure is also apparent for all the samples and temperatures.

3.7 Failure Location

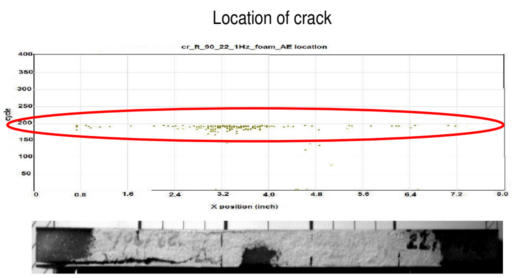


Fig. 13. 1-D Damage Location plot for CF/RC at 90% load and RT

The two AE sensors were mounted on the core to obtain location plots such as those in Figure 13. The results compare very favorably with the physical results. When the sensors were placed on the skin, the results were significantly noisier..

## 4. Conclusions

The AE amplitude parameters were found to closely echo the mechanical test results. Failure across the samples tended to follow the pattern of amplitude increases with viscoelastic matrix deformation and damage reaching a climax at the break point. The failure mode across the samples was core shear under static loading at the different temperatures.

AE seems to capture much more details than most other monitoring methods, and the damage progression and failure history can be re-constructed to an almost limitless degree of precision and detail, with faithfulness to the mechanical test results. In cases of composite sandwich materials at lower temperatures, where very rapid failure mechanisms may manifest, AE seems to be an invaluable method to surely capture these and also analyze them in various ways.

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## References:

[1] Mizutania, Y., Nagashimaa, K., Takemotoa, M., Ono, K., "Fracture mechanism characterization of cross-ply carbonfiber composites using acoustic emission analysis," *NDT&E International* **33**, 101–110, 2000.

[2] Hamstad, M. A., "An examination of AE evaluation criteria for aerospace type fiber/polymer composites," *Proceedings of the 4th International Symposium on AE from Composite Materials (AECM-4)*, ASNT, 436–49, 1992.

[3] Nixon, J.A., Phillips, M. G., Moore, D. R., Prediger, R. S., " A study of the development of impact damage in cross-ply carbon fibre/PEEK laminates using acoustic emission," *Composites Science and Technology*, **31**(1):1–14, 1988..

[4] Valentin D, Bonniau P, Bunsell A. R., "Failure mechanism discrimination in carbon fibre-reinforced epoxy composites," *Composites,* **14**(4), 345–5, 1983.

[5] M. A. Hamstad, A. O'Gallagher and J. Gary, "Examination of the Application of a Wavelet Transform to Acoustic Emission Signals: Part 2. Source Location," *J. of Acoustic Emission*, **20**, 62-8, 2002.

[6] Ni, Q.-Q and Iwamoto, M., "Wavelet transform of acoustic emission signals in failure of model composites," Engineering Fracture Mechanics, 69, 717-728, 2002.

[7] Surgeon, M. and Wevers, M., "Modal analysis of acoustic emission signals from CFRP laminates," NDT & E International, **32**, 311 – 322, 1998.

[8] Kotsikos, G., Evans, J. T., Gibson, A. G. and Hale, J.M., "Environmentally enhanced fatigue damage in glass fibre reinforced composites characterized by acoustic emission," Composites: Part A: Applied Science and Manufacturing, 31 (9), 2000.

[9] Qi, G., "Wavelet-based AE characterization of composite materials," NDT & E International, **33**, 133 – 144, 2000.

[10] Dzenis, Y. and Saunders, I., " On the possibility of discrimination of mixed mode fatigue fracture mechanisms in adhesive composite joints by advanced acoustic emission analysis," International Journal of Fracture, 117, 123-128, 2002.

[11] Johnson, M., "Classification of AE transients based on numerical simulations of composite laminates," NDT & E International, **36** (5), 133 – 144, 2000.

[12] Choi, N.-S., Woo, S. C., Kim, T. W., and Rhee, K. Y., "Monitoring of failure mechanisms in fiber reinforced composites during cryogenic cooling by acoustic emission," International Journal of Modern Physics B, 17(8,9), 2003.

[13] Steel, J. A., Reuben, R. L., Hamlin, M. and Brown, E.R., Proceedings of the Institution of Mechanical Engineers, Journal of Materials, Design and Application, (218)1, 9-17, 2004.

[14] Ramirez-Jimenez, C.R., Papadakis, N., Reynolds, N., Gau, T.H., Purnell, P. and Pharaoh, M.,

"Identification of failure modes in glass/polypropylene composites by means of the primary frequency content of the acoustic emission event," Composites Science and Technology, 64, 1812-1827, 2004.
[15] Silva, F.E., Goncalves, L. L., Fereira, D.B.B., and Rebello, J.M.A., "Characterization of failure mechanism in composite materials through fractal analysis of acoustic emission signals," Chaos, Solitons and Fractals, 26, 481-494, 2005.
[16] Quispitupa, A., Shafiq, B., Just, F. and Serrano, D., "Acoustic emission based tensile characteristics of sandwich composites," Composites Part B: Engineering.(35), 563-571, 2004.
[17] Leone, C., Caprino, G. and de Iorio, I., "Interpreting acoustic emission signals by artificial neural neworks to predict the residual strength of pre-fatigued GFRP laminates," Composites Science and Technology, (66), 233-238, 2006.
[18] Bourchak, M., Farrow,I. R., Bond, I. P., Rowland, C. W. and Menan, F., "Acoustic emission energy as a fatigue damage parameter for CFRP composites," International Journal of Fatigue, (29), 457-470, 2007.