Acoustic Emission Study of Fiber Orientations on Fiber-Metal Laminates under Monotonic Tensile Loading

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ACOUSTIC EMISSION STUDY OF FIBER ORIENTATIONS ON FIBER-METAL LAMINATES UNDER MONOTONIC TENSILE LOADING

THESIS
Submitted in Partial Fulfillment of the Requirements for the degree

Master of Engineering (Mechanical)
at
The City College
of the
City University of New York

By
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Approved:

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Abstract

This paper studies the effect of fiber orientation on GLARE (glass fiber reinforced laminates) under tensile loading. Failure modes are investigated using both stress-strain relations and acoustic emission (AE) signals. These signals were analyzed and used for categorizing various types of microdamage, such as yielding, matrix cracking, matrix debonding, fiber pull-out, and fiber fracture. Experiments showed that different types of GLARE composite produced significant different AE profiles. Furthermore, AE parameters, such as peak amplitude, counts, duration, and frequency, were analyzed to give a much more in-depth explanation on failure mode.

Keywords: Acoustic emission (AE), GLARE, fiber metal laminate (FML), failure mode, non-destructive testing and evaluation (NDT&E)
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Nomenclature

\( n \)  
Number of fiber-reinforced epoxy laminae

\( m \)  
Number of aluminum alloy layers

AE  
Acoustic Emissions

GLARE  
Glass-fiber reinforced laminate

ARALL  
Aramid reinforced aluminum laminate

FML  
Fiber Metal Laminate

PDT  
Peak Definition Time (\( \mu \text{sec} \))

HLT  
Hit Lockout Time (\( \mu \text{sec} \))

HDT  
Hit Definition Time (\( \mu \text{sec} \))

GFRP  
Glass-fiber reinforced polymer

CFRP  
Carbon-fiber reinforced polymer

\( N_c \)  
Normalized cumulative counts

\( AE_{\text{Glare}} \)  
Total AE signals generated by Glare panel

\( AE_{\text{Al}} \)  
AE generated by aluminum panel

\( AE_{\text{preg}} \)  
AE contributed by prepreg layers

\( AE_{\text{preg}90} \)  
AE contributed by prepreg layers oriented in the tranverse direction

\( AE_{\text{preg}0} \)  
AE contributed by prepreg layers oriented in the longitudinal direction

\( t_{al} \)  
Total thickness of aluminum layers

\( t_{fml} \)  
Total thickness of laminate layers

\( dB \)  
Decibels
1. Introduction

Glass fiber reinforced laminate (GLARE) is a type of fiber metal laminate (FML) currently used in the upper fuselage and on the stabilizers’ leading edge of Airbus A380. It has been researched and studied for over forty years. FML began with the study of aramid-reinforced aluminum laminate (ARALL), which showed excellent fatigue, impact, and damage tolerance characteristics. Aside all the improved properties compared to monolithic aluminum, the main reason for FML research was that it was possible to have a 20% weight reduction. On the contrary, it was a highly complex product for usage in a military aircraft. It required more manufacturing processes, thus making the laminate very expensive compared to aluminum. As more research was done on GLARE, it became a much more promising composite material used in aircrafts due to the lowering manufacturing cost [1].

Acoustic emission (AE) is a passive non-destructive testing (NDT) method for detecting and monitoring damage within a structure. It is generated through stress or pressure waves during the dynamic processes within materials [2]. Other non-destructive evaluation (NDE) such as ultrasonic testing are capable of examining defects and damage within a material, whereas AE is used for active detection of the activities inside the material, thus making it a better fit for health monitoring of structures.

As the usage of composite increases in structures, AE is particularly useful in damage detection. Because damage often occurs within the composite, visual inspection might not be an option to locate damage. With the use of AE technique, damage such as matrix cracking, delamination and fiber breakage can be predicted early enough to prevent unexpected failure.
2. Acoustic Emission

Acoustic emission sensing is a passive non-destructive testing technique used to monitor the health of a material as it undergoes various stresses during its life-cycle. Failures in the material are accompanied by the release of energy as intermolecular bonds break and shift. Each release of energy produces a transient elastic wave that is transmitted through the material and may be detected and recorded with surface-mounted transducers.

![Figure 1 An AE signal with basic terminology](image)

The acoustic events (also referred to as 'hits') are characterized by a variety of different parameters that may be used to infer the type of failure mechanism taking place in the material. Data recording is triggered in the AE software when vibrations in the material cross a certain threshold level. Further vibrations that cross this threshold are recorded and tallied as 'counts' that belong to a given hit. Each hit is also characterized by the maximum amplitude achieved by any one of its particular counts. Additional quantities recorded include the hit's duration, rise time and absolute energy (found by integrating the signal's amplitude over the hit's duration), as shown in Fig. 1.
In many instances, a hit may be made up of signals from several different events arriving at a transducer simultaneously. For this reason, there are no definitive algorithms to automate interpretations of the signals received, and a certain degree of deduction must be employed when interpreting the signals to understand the causes of the acoustic events [3]. Certain failure mechanisms, however, have been experimentally isolated and their acoustic qualities been quantified in order to give us an idea of the types of damage being incurred in a stressed material [4,5,6]. Additionally, new research with neural networks are finding more robust multi-parameter descriptions of acoustic events [3,7].

Another promising use of acoustic emission equipment is to find correlations between the rate of accumulation of acoustic activity with the residual strength in a given material. Caprino et al. [8] have shown that correlation curves based on A.E. activity can be experimentally determined and then used to determine a material's residual strength based on the rate of acoustic activity accumulation.
3. Material Description

All of the specimens tested in this study are under the standard grade GLARE 5. The specimens are defined as GLARE 5 FML, due to the fact that there are a total of two prepreg layers. In addition, within each prepreg there are four layers of fibers stacked symmetrically [1], shown in the table below. Five types of specimens were tested. Each one of the five types has a specific fiber orientation. They are all composed of continuous S-glass fiber reinforced epoxy laminae interleaved with aluminum alloy 2024-T3 sheets. Each prepreg layer consists of 59% in nominal fiber volume fraction, and bonded to the aluminum sheets with FM 94 adhesive. Fibers orientations are shown in the table below.

<table>
<thead>
<tr>
<th>Panel #</th>
<th>Grade</th>
<th>Configuration (m/n)</th>
<th>Prepreg Plies &amp; Orientations</th>
<th>Prepreg Thickness (mm)</th>
<th>Total Thickness (mm)</th>
<th>MVF</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>GLARE 5</td>
<td>3/2</td>
<td>[0/90]₁</td>
<td>0.024</td>
<td>0.076</td>
<td>0.36</td>
</tr>
<tr>
<td>11</td>
<td>GLARE 5</td>
<td>3/2</td>
<td>[0/0]₁</td>
<td>0.024</td>
<td>0.076</td>
<td>0.36</td>
</tr>
<tr>
<td>12</td>
<td>GLARE 5</td>
<td>3/2</td>
<td>[90/90]₁</td>
<td>0.024</td>
<td>0.076</td>
<td>0.36</td>
</tr>
<tr>
<td>13</td>
<td>GLARE 5</td>
<td>3/2</td>
<td>[+45/-45]₁</td>
<td>0.024</td>
<td>0.076</td>
<td>0.36</td>
</tr>
<tr>
<td>14</td>
<td>GLARE 5</td>
<td>3/2</td>
<td>[0/+45/-45/90]</td>
<td>0.024</td>
<td>0.076</td>
<td>0.36</td>
</tr>
</tbody>
</table>

*Table 1* Fiber configuration on different types of specimens in experiment

Under the standard grade, specimens can be further distinguished by defining its *m/n* layup configuration, in which *m* denotes the total number of aluminum alloy plies, and *n* represents the number of GFR epoxy prepreg. Within each GFR epoxy prepreg, it consists of four fiber layers. Their fiber orientations are listed under prepreg plies & orientation, and 0° represents the same direction as the rolling direction of the aluminum alloy. Each configuration is assigned a panel number, as we will refer to in discussion. Each layer is stacked symmetrically, as represented by
the subscript \( s \) outside of the fiber orientation brackets, with the exception of panel 14, a quasi-isotropic sample with GRF layers in four different directions.
4. Testing Equipment and Procedure

Tensile testing was done in an MTS 810 22-kips universal testing machine equipped with hydraulic grips. All specimens were subjected to displacement controlled monotonic tensile loading at a constant crosshead displacement rate of 0.05 inches/minute (2 mm/min) consistent with ASTM standard D3039. Tests were conducted at room temperature.

All panels were tested with a 10 kip load cell, with the exception of panel 11, which required a higher-capacity 20 kip load cell due to its $[0^\circ/0^\circ]$ fiber orientation. Displacement was measured with a 2.5 inch displacement cartridge. Data from the MTS machine was collected in a National Instruments data acquisition board.

Multiple samples from each test panel were cut into 1” x 10” tensile specimens. All cutting was done using a diamond bladed tile saw, which provided a reasonably smooth finish at the cutting edges.

To prevent the ends of the samples from incurring damage from the serrated grips of the tensile tester, protective tabs of 80-grit emory paper were glued to the ends of the sample. While only the outer two ends of each sample were held in the grips, the protective tabs covered three inches.

![Figure 2 Sample set-up with transducers](image)
of each end in order to provide a smoother transition for shear between the tabs and the sample. The tabs were bonded to the samples using 3M ScotchWeld\textsuperscript{©} dp810 acrylic adhesive which was then allowed to cure for at least 24 hours before testing.

Tranducer used was Physical Acoustics piezoelectric wide-band differential transducers (WD sensors) with 100-1000 kHz bandwidth. A sensor was mounted to one side of the specimens, at a distance of one inches from the sand paper.

In order to eliminate possible signal distortion caused by air pockets, a silicone couplant is typically used on the sensor surface. We opted instead for the use of hot-glue to serve as a couplant as well as a way to attach the sensor to the specimen. Ideally this method of attachment would have been adequate, but the energy released at specimen failure was often sufficient enough to throw the sensor off of the samples and into the walls of our environmental chamber. For this reason, electrical tape was used as a second restraint for the sensor to help ensure its longevity.

To minimize the addition of environmental noises to our data, tests were carried out in an environmental chamber lined with 1” thick flexible polyurethane acoustical foam absorber.

For signal conditioning, PAC (Physical Acoustics Corporation) model 2/4/6 preamplifiers, set to 40 dB gain were employed. The resulting signals were sent to a 4 channel PAC PCI-DSP data acquisition board which collected the data at a sampling rate of 10MHz.

The raw data was acquired and pre-processed using PAC's AEwinPost software. Filtered data
Figure 3 AE data collection system

describing selected parameters of each acoustic event were then exported to an ASCII file so that further statistical analysis could be performed in Matlab. Load-Displacement data from the MTS machine was collected by a National Instruments data acquisition board and pre-processed with Labview software. MTS data was synchronized with the AE data when running analysis in Matlab.

Calibration of the Acoustic Emission sensors was checked using the Auto Sensor Test utility provided in the AEwinPost software.
5. Experimental results and observations

5.1 General observations

Stress strain curve is often very useful in characterizing the material's behavior under loading. It can also yield important information about the material's properties. For composite materials, it is directly related to the fiber orientations. We can see how the orientation of fibers strengthens or weakens our GLARE composite, as shown in Figure 4.

\[ \text{\boldsymbol{\sigma}} \text{-} \varepsilon \text{ curve comparison} \]

On the contrary, stress strain curve does not provide enough information on how the material undergoes various stages of failure. With the aid of acoustic emission, it provides an insight to what type of microdamage occurs, as well as characterizes the stages of failure in GLARE. By associating stress strain curve with its AE profile, we can identify the types of damage that occur at different stages, and possibly predict failure.

Figure 4 Overall comparison of stress-strain curve between panels
As shown in Figures 5 to 14, the mechanical behaviors and acoustic emissions are plotted together for analysis. Due to the high number of tests conducted, as well as multiple channels used for collecting AE data, the selected few have very similar magnitudes of cumulative counts. The longitudinal stress, as well as the AE signals, are plotted against the longitudinal strain. AE data are presented in terms of its cumulative counts, in which it describes the overall history of microdamage. As described in testing procedure, the use of four AE sensors increases the likelihood of obtaining data near the point of fracture. Thus the mode of failure within each panel type are relatively similar, leading to the similarity of AE responses. On the contrary, defects, such as voids and porosity, exist in all types of composite material, which will attribute to the minor difference in counts, duration, and other AE parameters. In addition, the distance between the sensor and the location of fracture will vary among tests, promoting dispersion and attenuation of AE signals.

A method commonly used during the analysis of AE signals is normalization. The process can remove statistical error that exists in the measurement of data. Both stress and strain were normalized using their respective value at fracture. For the case of AE cumulative counts, the value taken for normalization was not at fracture; due to the release of localized stress energy at fracture, the AE signals are high in counts and amplitude, which results in a abrupt increase in data curve. Normalized curves will only serve the purpose of the determination of curve fitting parameters, thus these constants will be applicable to any sets of data from one panel. Figure 6 shows the improvement after normalizing the raw data.
Figure 5 Panel 5’s stress-strain curve and AE cumulative counts for two tensile tests

Figure 6 Panel 5’s normalized stress-strain curve and AE normalized counts for two tensile tests
Figure 7 Panel 11’s stress-strain curve and AE cumulative counts for two tensile tests

Figure 8 Panel 12’s stress-strain curve and AE cumulative counts for two tensile tests
Figure 9 Panel 13’s stress-strain curve and AE cumulative counts for two tensile tests

Figure 10 Panel 14’s stress-strain curve and AE cumulative counts for two tensile tests
6. Panel Discussion I

Among the five different types of GLARE composites that were tested, we can categorize them into two main groups, based on their stress strain relations and AE profiles. Group I consists of three panels that have fibers oriented in the tensile direction. All three panels contain $0^\circ$ fiber reinforced prepreg, but with different numbers of $0^\circ$ fiber reinforced layers. All of them show stress strain curve with close resemblance to a piece-wise linear stress strain curve with moderate tangential modulus. Group II consists of two panels that do not have any fibers along the loading direction, thus their ability to carry load is much less compared to Group I.

The three panels that exhibit similar stress-strain behaviors, as well as AE profiles, are panel 5, 11 and 14. Panel 11, representing GLARE 5 3/2 with all fibers oriented in the $0^\circ$ direction, has the highest Young's modulus among all of the tested specimens. It is simply because of the fact that the fibers are oriented in the same direction of the applied stress. However, due to the fact that it is only strengthened unidirectionally, it implies that it has a relatively low transverse stiffness. In other words, when the fibers reaches its maximum tensile stress, the aluminum layers will take up most of the load. In common composite material design, fibers often have a much higher strength than the matrix, thus the specimen will completely fail when it reaches fiber fracture. Panel 11's AE profile can be described using two curve fitting functions. Initially, it has an exponential growth of normalized AE cumulative counts, approximated by the equation

$$N_{c_1} = Ae^{ae}$$

where $N_{c_1}$ represents the normalized cumulative counts for the first region, $A$ is a constant, $\alpha$ is the exponential coefficient, and $\epsilon$ is our normalized strain. It is then followed by a power growth, approximated by the equation...
\[ Nc_{II} = B \varepsilon^\beta \]

where \( Nc_{II} \) is the normalized cumulative counts for the region before final failure, \( B \) is a constant, and \( \beta \) is the power coefficient. These curve fitting functions were estimated and plotted with the original data as shown in Figure 15. Both panels 5 and 14 have the same trend in AE profile, leading to the assumption that similar microdamage and failure mode occurred in all three of them.

![P11 Normalized \( \sigma \)-\( \varepsilon \) curve with AE data comparison](image)

*Figure 11 Panel 11’s normalized stress-strain curve with curve-fitted normalized AE profile*

Panel 5, namely GLARE 5 3/2 with fibers in both 0° and 90°, also shows a similar stress-strain behavior. But due to the fact that there are layers of prepreg with fibers in the transverse direction, one would expect that the aluminum layers must take a higher portion of the load compared to panel 11. As a result, aluminum undergoes yielding earlier, which led to the increase exponential growth of cumulative counts, shown below in Figure 16. The curve fitting functions are the same as panel 11, and their values are tabulated in table 2 for comparison.
Panel 14, with the configuration of $[0^\circ/45^\circ/-45^\circ/90^\circ]$, is the quasi-isotropic panel that has the lowest stiffness in Group I. It is mainly because of the fact that we are performing tensile testing, with only two layers of $0^\circ$ fibers reinforcing its prepreg. It is manufactured for the main purpose of increased impact resistance. In this study, it is of interest to investigate the effect of fiber orientations with respect to its AE profile. The curve fitting functions are again the same as panel 5 and 11. In comparison with panel 5, it indicates that the aluminum layers shared part of the load with the composite layers, which leads to the early yielding of aluminum. This is indicative from the values shown in table 2. Both panel 5 and 11 has a higher exponential coefficient, representing signals emitted from aluminum yielding. We can also see that it has a very similar cumulative counts profile as panel 5, as shown in Figure 17. Even though the cross-angle fibers are not aligned in the direction of tension, they aid in taking part of the shear stress. It does not undergoes any abrupt failure, instead it fails gradually with time. Aluminum yielding, matrix cracking, fiber debonding, and fiber fracture all occur steadily with increasing load.
**P14 Normalized σ-ε curve with AE data comparison**

![Graph of normalized stress-strain curve with AE data comparison](image)

*Figure 13 Panel 14’s normalized stress-strain curve with curve-fitted normalized AE profile*

<table>
<thead>
<tr>
<th>GLARE grade (Panel #)</th>
<th>E (GPa)</th>
<th>$\sigma_u$ (MPa)</th>
<th>$\varepsilon_u$</th>
<th>$\sigma_Y$ (MPa)</th>
<th>$\varepsilon_Y$</th>
<th>$\sigma_{\text{Knee Point}}$</th>
<th>$%\sigma_{\text{Knee Point}}$</th>
<th>$\varepsilon_{\text{Knee Point}}$</th>
<th>Total Cumulative Counts</th>
<th>Exponential coefficient $\alpha$</th>
<th>Power coefficient $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE 5 3/2 [0/90], (Panel 5)</td>
<td>38.584 ±1.73</td>
<td>742.55 ±18.39</td>
<td>0.0573 ±0.0021</td>
<td>259.51 ±10.98</td>
<td>0.00872 ±0.00034</td>
<td>672.84</td>
<td>91.67%</td>
<td>0.4926</td>
<td>171,323 ±4.39%</td>
<td>2.47850, (0.617)</td>
<td>3.5766, (0.8939)</td>
</tr>
<tr>
<td>GLARE 5 3/2 [0/0], (Panel 11)</td>
<td>42.119 ±1.75</td>
<td>1188.1 ±77.87</td>
<td>0.0658 ±0.0146</td>
<td>323.56 ±4.00</td>
<td>0.00968 ±0.00024</td>
<td>995.25</td>
<td>79.45%</td>
<td>0.04823</td>
<td>346,518 ±28.96%</td>
<td>1.7495, (0.04595)</td>
<td>4.1406, (0.65705)</td>
</tr>
<tr>
<td>GLARE 5 3/2 [0/+45/-45/90], (Panel 14)</td>
<td>31.70 ±1.92</td>
<td>456.38 ±23.43</td>
<td>0.0523 ±0.002</td>
<td>190.66 ±11.82</td>
<td>0.00801 ±0.00007</td>
<td>423.10</td>
<td>93.17%</td>
<td>0.4615</td>
<td>134,145 ±14.33</td>
<td>2.17850, (0.08817)</td>
<td>3.1434, (0.9059)</td>
</tr>
</tbody>
</table>

**Table 2 Group 1 panels (5,11,14) properties and curve fitting parameters**

From the above table, we can see that panel 11 has the highest number of counts. It corresponds to the increase in amount of acoustic signals when there is more fiber breakage. We can also observe that the power coefficient is indicative when there is a higher number of fiber fracture; the higher the coefficient, the larger the number of fiber fracture occur in region C.
7. Panel Discussion II

As mentioned earlier, Group II specimens do not have any fibers in the direction of tensile load. Their stress strain behavior are very similar to aluminum. Panel 12 has all of its fibers in the transverse direction, as shown in table 1. Since the applied load is perpendicular to the fibers, the stress it induced only get distributed to the aluminum and the epoxy. Research done on brittle matrix composites have suggested that damage progression in tensile samples follows a typical pattern: matrix crack initiation, crack propagation and fiber/matrix de-bonding, then fiber fracture preceding final failure [8]. As we expected, it has the lowest young’s modulus, owing to the fact that the fiber essentially did not add any stiffness to the composite. In comparison to Group I, its AE profile shows much difference (Figure 18), as the microdamage pattern has become dominant in yielding of aluminum and matrix cracking. It has an exponential saturation profile for its initial stage of stress localization, approximated by

\[ Nc_a = \alpha_0[1 - e^{-\beta_0(e-x_0)}] + Y_0 \]

where \( \alpha_0 \) is the steady-state value, \( \beta_0 \) is the exponential saturation rate, \( X_0 \) and \( Y_0 \) are offsets. It is followed by another exponential saturation profile prior to its final failure, with equation of form

\[ Nc_{II} = \alpha_1[1 - e^{-\beta_1(e-x_1)}] + Y_1 \]

where \( \alpha_1, \beta_1, X_1, Y_1 \) are the curve fitting parameters for the region between 0.5 normalized strain to final failure.
As for panel 13, which has the configuration of [+45/-45°]_s in its prepreg, shows only a slight increase in Young's Modulus; it implies that the fibers did not aid in stiffening the epoxy matrix. On the contrary, it caused the shear stress to propagate along the fiber's direction, causing matrix cracking parallel to the fibers [9]. Thus the panel failed in shear mode. Its AE profile is different to that of panel 12. It has an exponential saturation in its initial stage (Figure 19), as the matrix begins to crack. The curve fitting function is identical to panel 12, written as

\[ Nc_I = \alpha_0 \left[ 1 - e^{-\beta_0 (\epsilon - \epsilon_0)} \right] + Y_0 \]

Before final failure occur, it has the same type of AE profile as Group I. The curve fitting function becomes

\[ Nc_{II} = B \epsilon \beta \]

This could be understood through the explanation of fiber pullout and breakage after the matrix has failed in shear, similar to Group I failure mode: fiber breakage. Their curve fitting
parameters are tabulated in table 3 and 4. The increase in panel 13’s saturation rate is possibly due to the increase amount of matrix cracking with little amount of fiber fracture.

![Figure 15 Panel 13’s normalized stress-strain curve with curve-fitted normalized AE profile](image)

**Table 3 Material properties of panel 12 and curve fitting parameters**

<table>
<thead>
<tr>
<th>GLARE grade (Panel #)</th>
<th>E (GPa)</th>
<th>$\sigma_u$ (MPa)</th>
<th>$\varepsilon_u$</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\varepsilon_y$</th>
<th>$\sigma$ @ Knee Point</th>
<th>$%\sigma$ @ Knee Point</th>
<th>$%\varepsilon$ @ Knee Point</th>
<th>Total Cumulative Counts</th>
<th>Exponential saturation coefficient $a_0$, $b_0$, $(X_0, Y_0)$</th>
<th>Exponential saturation coefficient $a_1$, $b_1$, $(X_1, Y_1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE 5 3/2 [90/90] (Panel 12)</td>
<td>28.91 ±0.63</td>
<td>220.52 ±20.76</td>
<td>0.0752 ±0.0106</td>
<td>187.09 ±3.58</td>
<td>0.00852 ±0.00023</td>
<td>206.17 ±95.53%</td>
<td>0.0752 ±0.0106</td>
<td>206.17 ±95.53%</td>
<td>61.435 ±0.97%</td>
<td>0.1948, 7.4379 (0.0901, 0.0232)</td>
<td>0.7823, 4.5735 (0.5112, 0.2785)</td>
</tr>
</tbody>
</table>

**Table 4 Material properties of panel 13 and curve fitting parameters**

<table>
<thead>
<tr>
<th>GLARE grade (Panel #)</th>
<th>E (GPa)</th>
<th>$\sigma_u$ (MPa)</th>
<th>$\varepsilon_u$</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\varepsilon_y$</th>
<th>$\sigma$ @ Knee Point</th>
<th>$%\sigma$ @ Knee Point</th>
<th>$%\varepsilon$ @ Knee Point</th>
<th>Total Cumulative Counts</th>
<th>Exponential saturation coefficient $a_0$, $b_0$, $(X_0, Y_0)$</th>
<th>Exponential saturation coefficient $a_1$, $b_1$, $(X_1, Y_1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLARE 5 3/2 [45/45] (Panel 13)</td>
<td>30.193 ±2.50</td>
<td>204.85 ±11.74</td>
<td>0.0456 ±0.0064</td>
<td>164.94 ±11.28</td>
<td>0.00745 ±0.00037</td>
<td>198.25 ±96.05%</td>
<td>0.00745 ±0.00037</td>
<td>198.25 ±96.05%</td>
<td>27.068 ±7.70%</td>
<td>0.5447, 6.0603 (0.200, 0.1477)</td>
<td>1.1402 (0.3129)</td>
</tr>
</tbody>
</table>

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8. AE signals Discussion I: Characterize microdamage based on AE parameters of GLARE with 0° fiber

Aside from AE cumulative counts analysis, we can look at other AE parameters to further understand the types of microdamage that occurs in GLARE material. Some of the parameters that will be discussed includes counts, amplitude, duration, and frequency. We have looked at how cumulative counts characterize the regions of microdamage. With the study of the signals' amplitude, we can further understand the events that are occurring. From cumulative counts, we can observe the number of events occurring, but it does not identify the type of microdamage. The type of failure can be described by the combination of counts and amplitude. Table 5 shows the estimation of correlation.

<table>
<thead>
<tr>
<th>Failure type</th>
<th>amplitude (dB)</th>
<th>count range</th>
<th>frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>matrix crack</td>
<td>40-55</td>
<td>1</td>
<td>200-500</td>
</tr>
<tr>
<td>crack propagation</td>
<td>50-65</td>
<td>2-20</td>
<td>75-150</td>
</tr>
<tr>
<td>interface fracture</td>
<td>65-90</td>
<td>20+</td>
<td>~100</td>
</tr>
<tr>
<td>fiber pull out</td>
<td>60-75</td>
<td>20+</td>
<td>~150</td>
</tr>
<tr>
<td>fiber fracture</td>
<td>90-100</td>
<td>25+</td>
<td>&gt;100</td>
</tr>
<tr>
<td>delamination</td>
<td>55-70</td>
<td>25+</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

*Table 5 Signal characteristics of primary micro-damage mechanisms*

Panel 11 shows a very distinct AE counts versus amplitude. As shown in Figure 20, we can see that matrix cracking, crack propagation, and interface fracture occur throughout the entire duration of the tensile test, until final failure is reached. For counts greater than 25 and amplitude above 56db, we see a huge cluster of data points prior to final failure. These high amplitude events could correspond to fiber fracture [4]. It indicates that fiber breakage emits high amount
of energy, leading to the high amplitude these signals have. We can also observe that at 4.5% strain, there are signs of fiber breakage. It corresponds to the minor drop in stress, which indicate that the load is further distributed among the aluminum and remaining fiber layers.

![AE events (amplitude) vs strain in panel 11, test 3](image)

*Figure 16 Panel 11's AE signal's amplitude distribution in relation to stress-strain curve*

We can also look at the signals’ duration to further identify the damage. In Figure 21, we can clearly see that prior to final failure, there is a large number of points at approximate 7.4% strain. This can be understood as the reverberation coming from the fiber breakage. The high-amplitude fiber breakage is much more dominant in terms of damage propagation, leading to other microdamage, thus increasing the duration of the hit.
We can also relate the signals amplitude with its duration. Figure 22 shows that short duration signals have a lower amplitude, and longer duration signals tends to emits more energy. It further explains the effect of fiber breakage on reverberation through the matrix and aluminum.
The previous type of AE behavior is also observed in panel 5 and 14. In panel 5, there are a total of four layers of fiber, making it half of what panel 11 is composed of. Its AE signals indicate that the amount of signals emitted from fiber breakage is much less than panel 11. In fact we can see from the failed specimens that they all failed perpendicular to the applied tension. As we have discussed earlier, the fibers in 90° did not increase the stiffness of the prepreg, rather it allowed stress to localize between these fibers, and promoted matrix cracking in the transverse direction.

![Figure 19 Panel 5's AE signal's amplitude distribution in relation to stress-strain curve](image)

A comparison between the amplitude and duration of the signals is also made, to further interpret the AE signals. Aside from the reduced amount of AE signals, it very much resembles panel 11's behavior. The only difference is that prior to final failure, it does not undergo two stage of fiber breakage. In fact, the failure of fibers in one prepreg almost immediately cause the failure of the other. The same phenomenon of reverberation is observed. These AE events are far longer than other microdamage events like matrix cracking and aluminum yielding. The fiber breakage can
lead to a duration as long as 5ms. But events that last this long are very rare, with only one or two data points.

**Figure 20** Panel 5's AE signals duration in relation to stress-strain curve

Panel 5's amplitude versus duration plot shows much similarity with panel 11's. Signals ranging from 100μs to 300μs has the same amplitude as signals that are longer in duration.

**Figure 21** Panel 5's AE signals' amplitude versus duration
In panel 14, we again expect a similar AE profile. With only 2 layers of fibers in the 0° direction, the signals from fiber fracture is far less than panel 11 and 5. Solely from the signals analysis does not provide enough information on the type of damage induced in the material, thus the signals' duration were far more useful. In Figure 27, we notice the tremendous drop in duration of AE signals. Fiber breakage is far less than in panel 11 and 5. In fact, the failure mode is in shear, suggesting that a high percentage of stress was transferred to the cross angle fiber layers. We still see the effect of reverberation from fiber breakage from signals at long duration, but most of the signals are clustered at lower duration around 200μs. This might indicate that fiber breakage in the cross plies were more severe, with less of the reverberation effect. When the fibers in 0° failed, the damage is sudden, accounts for the high volume of fiber breakage and prolongation of sound. When the fibers in ±45° failed, the damage is not as abrupt, thus its signals are much shorter in duration. We can further witness this microdamage behavior with Figure 28. The signals' peak amplitude increases non-linearly with duration. Signals with only 100μs of duration reaches 80dB in amplitude. All panels in Group 1 exhibit this behavior, suggesting that with aluminum yielding and matrix cracking, with addition of localize fiber breakage, signals will have a high amplitude even at low duration.
Figure 22 Panel 14’s AE signal’s amplitude distribution in relation to stress-strain curve

Figure 23 Panel 14’s AE signals duration in relation to stress-strain curve
Figure 24 Panel 14's AE signals' amplitude versus duration
9. AE signal Discussion II: Characterize microdamage based on AE parameters of GLARE with fiber in 90° & ±45°

As discussed earlier, panel 12 has a very unique AE profile, compared to all other panels. All of the specimens failed perpendicular to the loading direction. We can see that there are high counts and amplitude during yielding, as well as 4% strain. It does not represent fiber breakage, but fiber debonding with the matrix epoxy. Shown in Figure 29, it is most visible at 4% strain, where the stress has localized inside the matrix, with more matrix cracking. From Figure 30, we can see that low amplitude counts constitute a major proportion of the signals. As shown in table 5, these signals accounts for matrix cracking. We can associate the matrix cracking with the failed specimen.

![AE events (amplitude) vs strain in panel 12, test 1](image)

*Figure 25 Panel 12's AE signal's amplitude distribution in relation to stress-strain curve*
Figure 26 Panel 12's AE signals duration in relation to stress-strain curve

Figure 27 Percentage of signals in increasing counts and amplitude categories
Panel 13’s AE signals showed very small amount of activities occurring during testing. The amount of signals with high amplitude are far less than Group 1, but fiber breakage still occurs during yielding and final failure. At approximately 0.1 normalized strain, we can see an increase in signals across different counts and amplitude. It indicates the propagation of crack, leading to matrix cracking and fiber breakage. We can also see from Figure 34 that majority of the signals have a duration of less than 400μs. Without much fiber breakage, the panel does not undergo reverberation, showing far less signals with much lower amplitude.
Figure 29 Panel 13's AE signal's amplitude distribution in relation to stress-strain curve

Figure 30 Panel 13's AE signals duration in relation to stress-strain curve
We can observe that panel 13's amplitude-duration correlation is very different from Group 1's. We can see that signals only have an amplitude of 60dB with a duration of 100μs. As the duration of the signal increases, the peak amplitude increases linearly. This behavior explains how fiber breakage can easily lead to other forms of internal damage. In this case, fiber breakage occurs far less frequent, thus it doesn't increase the likelihood of reverberation.

Figure 31 Panel 13's AE signals' amplitude versus duration
10. Conclusions

This paper studies the correlation between GLARE composite's stress-strain behaviors and acoustic emission signals under monotonic tensile loading. AE signals produced by microdamage during testing provided us an insight into the categories of damage, such as plastic deformation, matrix cracking, debonding, and fiber fracture. Different prepreg layups also provided a mean for understanding and analyzing the AE signals and their interrelations. By utilizing our current knowledge on AE count profiles, we can assess failure to some degrees of certainty. The state of stress can be associated with the amplitude of the signals, to identify the damage severity. Besides analyzing the amplitude, we can also study the duration of the hits, as it indicates a specific type of microdamage. Signal duration can also be associated with the amplitude of signal, which further aids in predicting microdamage occurrences.
Reference


