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Isolating Failure Mechanisms in a Fiberglass/Epoxy Tensile Test Specimen Using Acoustic Emission Signal Parameters

Michael Kouvarakos

Embry-Riddle Aeronautical University - Daytona Beach

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ISOLATING FAILURE MECHANISMS IN A FIBERGLASS/EPOXY
TENSILE TEST SPECIMEN USING ACOUSTIC EMISSION
SIGNAL PARAMETERS

by

Michael Kouvarakos

A Thesis Submitted to the
Office of Graduate Programs
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aerospace Engineering

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Eric v. K. Hill, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Office of Graduate Programs and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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ABSTRACT

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This study used acoustic emission (AE) signal parameters to isolate the failure mechanisms in a 0° unidirectional, fiberglass/epoxy tensile test specimen. Since several failure mechanisms were known to be present, the lack of any distinctly identifiable bands in the original amplitude distribution indicated that there was considerable overlap between the AE signals of the various failure mechanisms. In order to separate the amplitude bands associated with each mechanism, it was necessary to sort on the duration of the AE signal. Two additional plots, counts versus amplitude and hits versus counts, were used to verify that the amplitude distributions were comprised of a single predominant mechanism. A total of seven failure mechanisms were isolated from the original data set, all but two having a shape similar to that of a normal distribution.
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1.0 INTRODUCTION

Acoustic emission (AE) is produced by the rapid release of strain energy from flaw growth activity in a stressed material. This energy release, which is in the form of a stress wave packet, causes a disturbance in molecules of the material as it radiates outwards from the source to the surface.

An AE sensor, which uses a piezoelectric element for transduction, senses this disturbance and converts this mechanical energy into an equivalent electric signal. Figure 1, shows the schematic of a typical AE test. The voltage signal, generated by the AE sensor, is amplified.

Figure 1. Schematic of an Acoustic Emission Test.
by 40 decibels (100x) through a preamplifier to boost the signal to a usable level. A bandpass filter is used to allow only signals within a certain frequency band, usually between 100 to 300 kHz for composites, to be processed. This eliminates low frequency background noise along with high frequency noise caused by electromagnetic interference. The amplified and filtered voltage signal is then fed to a data acquisition system for analysis. The data acquisition system extracts information about the signal and generates quantification parameters such as amplitude, counts, duration, rise-time and energy. These parameters are displayed on the computer screen in the form of correlation graphs or numerical tables.

As a nondestructive technique, AE differs from other nondestructive methods in many ways. First, the signal, used for analysis, is emitted directly from the source itself rather than being supplied by the nondestructive test method, as in ultrasonics or radiography. Second, flaw growth can be detected the instant it occurs under actual loading conditions, instead of requiring extensive down time for post analysis and inspection. Thus discontinuities can be monitored in real time from inception to specimen failure. Acoustic emission has been proven successful in many industrial applications including leak detection, proof testing, on-line monitoring, and in-service (requalification) testing [1].
Acoustic emission has also been used successfully as a tool in developing equations to predict the ultimate strength of composite materials. Research by Hill [2] and Kalloo [3] has demonstrated that burst pressures can be predicted in filament wound composite pressure vessels from AE data. Hill used AE energy and amplitude measurements to predict burst pressures in fiberglass/epoxy pressure vessels. Kalloo used AE amplitude bands to separate the failure mechanisms, then applied multivariate statistical analysis to predict burst pressures for graphite/epoxy pressure vessels. A similar approach was used by Walker [4] to predict ultimate strengths in graphite/epoxy composite tensile test specimens. Walker generated an ultimate strength prediction equation using a multivariate statistical analysis based on the low amplitude portion of the AE data.

As will be discussed later, there are many failure mechanisms associated with deformation and failure in composite materials. The signal received by the sensor is quantified by the computer using AE parameters which characterize the waveform. In each case, there is a direct correlation between the failure mechanisms and the magnitude of the various AE parameters, i.e., each mechanism has a characteristic signature. If there was only one failure mechanism present, all of the signals would be grouped within characteristic parameter bands. Typically, there
are several source mechanisms present, which together release thousands of signals. Oftentimes, overlap exists in the AE parameters of the various failure mechanisms such that there are no discrete bands observable in the data. Overlap could result from signal attenuation, closely occurring emissions of different sources, and equipment timing parameters. This paper takes the overlapped, original AE data and isolates each failure mechanism by filtering on the duration of the AE signal, then verifies the results using AE counts.
2.0 ACOUSTIC EMISSION SIGNAL IDENTIFICATION

2.1 ACOUSTIC EMISSION PARAMETERS

When a material is overstressed, AE stress waves are released from the flawed area. Through the use of an AE transducer, these stress waves are converted to an AE signal which resembles a complex, damped, sinusoidal voltage. This signal or hit typically has a fast rise-time to the peak amplitude followed by a slow exponential decay. In order to quantify this signal, certain key AE signal parameters are used. These are amplitude, duration, counts, rise-time, and energy.

Figure 2 shows a typical AE signal along with its quantifying parameters. An adjustable threshold voltage is set by the system operator to eliminate any unwanted background noise. An AE hit is processed by the computer when the voltage signal first exceeds the threshold (which signifies the beginning of the hit). The hit terminates when the voltage signal drops below the threshold and remains there for a set period of time. Each of the previously mentioned AE parameters are briefly described below.
Figure 2. Signal Waveform Parameters [1].

Amplitude: The peak of the voltage signal (hit), measured in decibels.

Duration: The time of the hit, from the first crossing of the threshold to the last crossing of the threshold, measured in microseconds.

Counts: The total number of times the voltage signal crosses the threshold in the positive direction.

Rise-time: The time, from the start of the hit to its peak amplitude, measured in microseconds.

Energy: The area under the rectified waveform, measured in energy counts.
2.2 INITIAL SETTINGS

Prior to beginning an AE test there are several key settings that need to be adjusted on the computer. These include the gain (amplification factor) and the threshold, followed by three timing parameters: the hit delay time (HDT), the peak detection time (PDT), and the hit lockout time (HLT). An explanation of each is discussed below.

The gain and threshold are established to dictate the magnitude of the AE signals to be processed by the data acquisition system. The gain amplifies the signal to a usable level. The threshold is set to eliminate any unwanted background noise.

The HDT is set to enable the system to determine the end of the signal. For example, if the HDT is set smaller than the time between the last crossing of the threshold of signal "A" and the first crossing of the threshold of signal "B", shown in Figure 3a, then signal "A" and signal "B" are registered as two hits. However, if the HDT is set larger than this time, then one hit with many counts will be registered. Figure 3b further illustrates the use of the HDT to eliminate reflections and measure only the main part of the wave. It is therefore very important to set the HDT so as to allow discrimination between each signal. The HDT setting also depends upon the type of
Figure 3. Illustrations of the HDT Timing Parameter [5].
test material used. For fiberglass/epoxy, the HDT is typically set between 100 and 200 microseconds [5]. An HDT value of 150 microseconds was used for this test.

The PDT, shown in Figure 4, is set to correctly identify the peak amplitude of the signal and to avoid false measurements being made on the high velocity, low amplitude precursor. Typical values for the PDT in fiberglass/epoxy range from 20 to 50 microseconds [5]. A value of 40 microseconds was used for this test.

![Figure 4. Illustration of the PDT Timing Parameter [5].](image)

The HLT, shown in Figure 5, activates after the termination of the HDT and locks out or eliminates any unwanted late arriving signals reflecting from sides or edges of the specimen under test. It also allows the system time to
reset the recording switches. The HLT is typically set at 300 microseconds for fiberglass/epoxy [5].

![HLT Timing Parameter](image)

**Figure 5. Illustration of the HLT Timing Parameter [5].**

### 2.3 FAILURE MECHANISMS

Composite materials exhibit very complex failure mechanisms when stressed. The three primary failure mechanisms are matrix cracking, fiber breaks, and delaminations. Each of these failure mechanisms can be characterized by observing the magnitude of the amplitude, duration, rise-time, counts, and energy resulting from the AE hit. Matrix cracking is usually the first primary failure mode to occur under uniaxial tension conditions. This is because the matrix (epoxy) is typically very brittle and is the weakest load carrying constituent of the composite specimen.
The purpose of the matrix is to hold the fibers in place and to distribute the load uniformly throughout the fibers.

There are two types of matrix cracking, transverse and longitudinal. Transverse matrix cracking (perpendicular to the fiber direction) hits exhibit low amplitude and energy with low counts and short duration [3]. Longitudinal matrix cracking (parallel to the fiber direction) hits exhibit medium amplitude and energy with high counts and long duration [3]. Transverse matrix cracking occurs throughout the loading period, due to the brittle characteristics of the resin. Longitudinal matrix cracking usually occurs as a result of insufficient fiber/matrix bond strength. This allows the transverse crack, propagating through the fiber or matrix, to turn 90° and travel parallel along the fiber direction.

The second primary failure mechanism is fiber breakage. The fibers are the primary load carrying constituents under tension. Fiber break signals characteristically exhibit medium to high amplitudes and energies with short to medium durations and low to medium counts [3]. As individual fibers break, more and more of the applied load is carried by the remaining intact fibers. Ultimately, these fibers also become overstressed and the specimen fails.
Delamination is the third primary failure mechanism; here, the individual layers of the specimen shear apart. Delaminations release very high amplitude, high energy signals with long durations and a high number of counts [3]. Delaminations occur where the interlaminar shear stresses are the greatest. They have been found to increase the burst pressure strength in some pressure vessels [2] through the stress relieving of individual layers. Delaminations mostly occur during flexural type loads (i.e. bending); very few occur from tension loads. Those that do occur are generally produced after serious fiber failure when the stress between the individual layers is the greatest.

Other sources also occur in composite specimens but can be thought of as subcategories to the primary mechanisms. These include plastic deformation of the matrix and fibers, fiber-matrix debonding and fiber pullouts [6].
3.0 EXPERIMENTATION

The tensile test specimen was constructed of eight layers of unidirectional Owens-Corning Fiberglass S-2 Glass cloth and a 45:100 ratio of Hexcel 2183 hardner to Hexcel Epolite 2410 resin using the wet layup method. The manufacturing procedure followed the ASTM D-3039 standard [7]. Additionally, one-eighth inch thick aluminum tabs were bonded to the ends of the specimen to otherwise prevent the serrated grips from digging into and wedging the tabs of the brittle composite material during loading, resulting in false signals and/or damaging the specimen. Also, without the aluminum tabs, the pressure applied by the grips could crush the ends of the specimen rendering it ineffective for testing.

A Physical Acoustics Corporation (PAC) model R15 (150 kHz) piezoelectric transducer was coupled and secured to the specimen using SAE 30 oil and electrical tape. As a couplant, the oil provides a good acoustical path for transmitting the stress waves from the specimen to the transducer. A PAC model 1220A preamplifier, used to amplify the signal above the noise level and to impedance match the transducer to the transmission cable, was next connected.
to the tranducer. The preamplifier was set at 40 dB with a band pass filter from 100 to 300 kHz. This frequency range is commonly used when testing composite materials, since it is between the lower frequency limit where background noise is detected and the upper frequency limit where wave attenuation becomes significant. The other end of the preamplifier was connected to a PAC LOCAN-AT system which contains the data acquisition system and the microprocessor.

Here, the data acquisition system includes the analog circuitry necessary to quantify the various AE signal parameters. The quantified signals are then displayed on the monitor for examination. Figure 6 shows the set-up of the AE system.

The LOCAN-AT hardware menu settings were as follows:

- **Gain:** 20 dB (plus 40 dB preamplifier = 60 dB total system gain)
- **Threshold:** 40 dB
- **PDT:** 40 microseconds
- **HDT:** 150 microseconds
- **HLT:** 300 microseconds
Finally, the specimen was placed between the serrated grips of a Materials Testing System (MTS) machine and ramp loaded, in tension along the fiber direction, to failure at a rate of 500 lbs/min.
Fiberglass/epoxy Test Specimen

Load  Tranducer (PAC Model R15)  Source  Load

\[ \text{Filter (100-300 kHz)} \]

\[ \text{Amplifier (40 dB)} \]

Preamplifier (PAC Model 1220A)

Data Acquisition System

Microprocessor

PAC LOCAN-AT

Keyboard  Monitor  Printer

Figure 6. Acoustic Emission Test Set-up.
4.0 PREVIOUS RESEARCH

There are several failure mechanisms that occur during the loading of a composite material. As previously mentioned, each failure mechanism can be characterized by the magnitudes of its AE signal parameters. It would be expected that the AE amplitude data, for instance, would show discrete amplitude bands, characteristic of each source. However, this was not the case as can be seen in Figure 7. Here the (differential) amplitude distribution

![Figure 7](https://example.com/figure7.jpg)

Figure 7. Hits Versus Amplitude (dB) Plot. Original Data.
is an exponentially decaying curve. The lack of any distinctly identifiable amplitude bands (failure mechanisms) indicated that there was considerable overlap between the various failure sources in the amplitude distribution data. It was therefore necessary to develop a process to separate the overlapping failure mechanism data.

Ely and Hill [8] showed that failure mechanisms in graphite/epoxy specimen could be separated into distinct amplitude bands by sorting on duration and rise-time of the AE signal. First, the low duration and rise-time signals were sorted, which isolated a low amplitude distribution. After removing these low amplitude hits, the duration and rise-time distribution plots revealed three distinct duration and rise-time intervals. Three separate filters were then performed on the three duration and rise-time intervals, resulting in the separation of three distinct failure mechanisms. These three failure mechanisms were found to consist of distinct amplitude distribution bands that were normally distributed. For this particular test the total system gain and threshold were set to 40 dB and 50 dB, respectively, giving rise to a total of 4725 hits recorded by the LOCAN-AT.
5.0 ISOLATION OF FAILURE MECHANISMS

The test material was a 0° (fiber angle) unidirectional fiberglass/epoxy composite specimen. The specimen was mounted on an MTS machine and a tensile load ramp of 500 lbs/min was applied parallel to the direction of the fibers until material fracture. The LOCAN-AT continuously monitored the AE activity from load onset to failure.

The specimen fractured at 5,880 lbs with a total of 22,582 hits recorded by the LOCAN-AT. Figure 7 shows the data graphed into a hits versus amplitude plot or (differential) amplitude distribution. The peak of 2,000 hits occurred at 40 dB (which coincided with the amplitude threshold setting of the LOCAN-AT), followed by an approximately exponential decay in the number of hits with increasing amplitude.

Hidden within this exponential distribution are several failure mechanisms, each represented by its own characteristic amplitude interval. A total of seven amplitude intervals were isolated. To be consistent with the terminology, the amplitude distribution with its peak located at the lowest amplitude value was labeled "Mechanism
1", the amplitude distribution with its peak located at the next highest amplitude value was labeled "Mechanism 2", etc.

Figure 7. Hits Versus Amplitude (dB) Plot. Original Data. (Repeated For Convenience.)

The resulting hits versus duration plot for the original data ranged from 0 to 20,000 microseconds. This duration span was broken down into three regions. Region I (lowest duration) contained Mechanism 1. Region II (highest duration) contained Mechanisms 6 and 7. Region III (mid duration) included Mechanisms 2, 3, 4, and 5. There will be a full explanation, in the upcoming subsection, on how each failure mechanism was isolated.
5.1 REGION I - MECHANISM 1

The first step was to isolate the lowest amplitude failure mechanism. Therefore, the first filter was set for a 0 to 40 microsecond duration interval, since these low amplitude signals had a characteristic shorter duration than the larger amplitude signals. To ensure that all of the Mechanism 1 hits were included, a second filter was performed, from 0 to 45 microseconds in duration. If the hits versus amplitude plot looked the same from both filters, all of the low amplitude signals were not "captured" by that filter; therefore, a second expanded filter would be needed. A shift in amplitude between the two graphs would then indicate that the range of the second filter was too large, since now the second filter included signals from a different mechanism. (It should be noted here that the rise-time parameter was not a factor in the separation of the different sources as it was for Ely and Hill [8].)

After several iterations, a duration interval from 0 to 55 microseconds (Region I) was found to isolate the lowest amplitude failure mechanism. The hits versus amplitude plot, shown in Figure 8, displays a single distribution with a peak amplitude at 40 dB. This single distribution represents a single failure mechanism, labeled Mechanism 1, with a total of 9,878 hits and 23,731 counts, resulting
in a counts/hit ratio of approximately 2. The distribution starts at about 35 dB and ends at 53 dB. The hits having amplitudes greater than 53 dB can be disregarded since they probably represent overlap from other mechanisms.

![Figure 8. Hits Versus Amplitude (dB) Plot.](image)

To verify that a single failure mechanism was predominant, two additional plots were used for comparison: (1) the counts versus amplitude plot and (2) the hits versus counts plot. Since these two plots are used extensively, a brief explanation of each is given here.

Because Mechanism 1 comprises the lowest duration hits, it is expected that the hits versus counts plot would show
a tendency toward a low number of counts per hit. In fact, if there is a single failure mechanism present the centroid of the hits versus counts plot should have a value equal to the counts/hit ratio calculated earlier. Therefore, it is expected that the peak of the counts versus amplitude plot would be the same as in the hits versus amplitude plot. Also, all three plots should be similar in shape (normally distributed). Conversely, for a region containing several failure mechanisms, it is expected that the hits versus counts plot would show more than one distinct peak. In this case, the counts versus amplitude plot and the hits versus amplitude plot will be dissimilar in shape.

Recall that the hits versus amplitude plot, Figure 8, showed that Mechanism 1 had a peak located at 40 dB. The counts versus amplitude plot shown in Figure 9 also had its peak at 40 dB with a similar shape to that of Figure 8. Here, the curves are not normally distributed because of the truncation provided by the threshold cutoff; as such, it is expected that the curves would be skewed to the right, which they are. Again, the hits having amplitudes greater than 53 dB are probably due to other failure mechanisms present. Figure 10 shows that the hits versus counts plot has its centroid at a value of approximately 2, the same as the counts/hit ratio calculated from the data of Figure 8.
Figure 9. Counts Versus Amplitude (dB) Plot.
Mechanism 1.

Figure 10. Hits Versus Counts Plot.
Mechanism 1.
These two verification plots (Figures 9 and 10) confirm that there is a single predominant failure mechanism present in Figure 8.

5.2 REGIONS II AND III

Having isolated Mechanism 1, it was then removed from the original data by filtering on durations greater than 55 microseconds. The result of this filter is the hits versus amplitude plot or amplitude distribution shown in Figure 11. This figure represents the original data without Mechanism 1. It has a peak at 49 dB and includes 12,704 hits and 260,187 counts, yielding a ratio of approximately

![Figure 11. Hits Versus Amplitude (dB) Plot. Original Data Without Mechanism 1.](image-url)
20 counts/hit. To prove that there is more than one failure mechanism buried within this large amplitude band, the corresponding verification graphs were examined.

Figure 12 shows the peak of the counts versus amplitude plot at 54 dB, which is different from the 49 dB peak seen in Figure 11. As a result, the shapes are also slightly different. This indicates that there are signals present from sources with different counts/hit ratios. The hits versus counts plot, shown in Figure 13, appears to have two peaks, one located at 10 counts and a second at 26 counts. It also has a much different shape than Figure

![Counts Versus Amplitude (dB) Plot. Original Data Without Mechanism 1.](image)
11; thus, there are at least two overlapping distributions (failure mechanisms) present.

Figure 13. Hits Versus Counts Plot.
Original Data Without Mechanism 1.

The verification plots disprove the presence of a single failure mechanism by having different peak and counts/hit values from the amplitude distribution (hits versus amplitude plot) plus different shapes.

5.3 REGION II - MECHANISMS 6 AND 7

The next step was to perform a filter on the high end of the durations of Regions II and III data from Figure 11. From the hits versus duration plot (not shown), it was
noticed that the majority of the hits occurred between 56 and 330 microseconds. There was, however, an extremely long flat tail on the right-hand end of this curve. This right-hand tail was labeled Mechanism 7. It consisted of 240 hits scattered between 331 to 20,000 microseconds and was flat in shape. Therefore, the verification plots were not needed.

Mechanism 7 was removed and the group of hits between 56 to 330 microseconds was analyzed in order to isolate the next mechanism. Several duration filters were tried, starting from 300 to 330 microseconds and decreasing incrementally to 180 to 330 microseconds, to ensure that all of the Mechanism 6 hits were included. The 180 to 330 microsecond duration interval resulted in the amplitude distribution shown in Figure 14. Note that it appears to be normally distributed. Mechanism 6 (as it was subsequently labeled) has a peak centered at 65 dB, a total of 2,476 hits and 81,258 counts that produced a high counts/hit ratio of 33. The amplitude band ranged from approximately 52 to 75 dB.

The counts versus amplitude plot from Figure 15 has a peak located at 65 dB, the same as the hits versus amplitude plot (amplitude distribution) of Figure 14. Although they may not immediately appear as such (due to the different
Figure 14. Hits Versus Amplitude (dB) Plot. Mechanism 6.

Figure 15. Counts Versus Amplitude (dB) Plot. Mechanism 6.
scales), these two graphs are virtually identical in shape. From Figure 16, the hits versus counts plot, a single normal distribution appears with a peak located at 31 counts, only 2 counts/hit lower than the ratio obtained from the amplitude distribution. The two verification plots indicate that the amplitude data of Figure 14 represents a single predominant failure mechanism.

![Figure 16. Hits Versus Counts Plot. Mechanism 6.](image)

5.4 REGION III - MECHANISMS 2 THROUGH 5

Mechanisms 6 and 7 were then removed from the amplitude distribution of Figure 11 by filtering on a duration interval from 56 to 179 microseconds. This yielded the
hits versus amplitude plot shown in Figure 17, which represents the original data without Mechanisms 1, 6 and 7. It has its peak located at 49 dB. The plot contains 9,988 hits and 155,332 counts for a counts/hit ratio of 16.

Figure 17. Hits Versus Amplitude (dB) Plot. Original Data Without Mechanisms 1, 6 and 7.

The two verification plots were again employed to prove or disprove that Region III contained a single failure mechanism. Figure 18 shows the counts versus amplitude plot. This graph has its peak located at 54 dB, 5 dB higher than the peak of Figure 17, meaning that there are two or more overlapping sources present. Additionally, the hits versus counts graph, shown in Figure 19, has its peak located at 10 counts, 6 counts less than the counts/hit
Figure 18. Counts Versus Amplitude (dB) Plot. Original Data Without Mechanisms 1, 6 and 7.

Figure 19. Hits Versus Counts Plot. Original Data Without Mechanisms 1, 6 and 7.
ratio of Figure 17. Moreover, the shape of the plot does not represent a simple normal distribution, but rather a composite shape, one that includes data from more than a single failure mechanism.

Because the Region III data (Figure 17) was found to contain at least two overlapping failure mechanisms within its duration range of 56 to 179 microseconds, the hits versus duration plot shown in Figure 20 was examined to see if there were any distinct duration bands such that duration filters could be used for mechanism sorting. Unfortunately, this graph provided no real assistance because there were no distinct duration intervals. Therefore, as before,
an iterative approach was used to determine the appropriate duration intervals.

5.4.1 MECHANISM 2. When the amplitude distribution of Figure 17 was filtered on the duration interval from 56 to 82 microseconds, the hits versus amplitude plot, shown in Figure 21, was generated. This amplitude band, labeled Mechanism 2, was subsequently proven to contain a single predominant failure mechanism. Mechanism 2 comprised 2,804 hits with 22,002 counts, resulting in a counts/hit ratio of approximately 8. The peak of the graph is centered at 45 dB and ranges from about 38 to 55 dB.

Figure 21. Hits Versus Amplitude (dB) Plot. Mechanism 2.
Figure 22 is a plot of counts versus amplitude, which has its peak at 45 dB, the same as the hits versus amplitude plot of Figure 21. It can be seen that these two graphs are also similar in shape.

![Counts Versus Amplitude (dB) Plot. Mechanism 2.](image)

The hits versus counts plot, shown in Figure 23, shows a normally distributed plot with a peak at 7 counts/hit, approximately the same as for the data of Figure 21. Again, this verifies the presence of a single predominant failure mechanism.
5.4.2 MECHANISMS 3 THROUGH 5. Mechanisms 3 through 5 were isolated from the Region III data in similar fashion. The details of these analyses are provided in Appendices A, B, and C.

5.5 SUMMARY

The method of sorting the data into the various failure mechanisms was as follows. First, the left hand end of the original amplitude distribution was analyzed (Region I). Isolating and removing Mechanism 1, which encompassed approximately 44% of the total data, facilitated the separation of the remaining failure mechanisms. Next,
the right hand end (Region II) of the original amplitude
distribution was investigated. This included Mechanisms
6 and 7. Once the left hand and right hand regions of
the amplitude distribution were removed, the middle region
(III) was analyzed. Region III was found to contain
Mechanisms 2 through 5.

Table 1 presents a summary of the AE parameter
characteristics for the seven failure mechanisms. It also
shows the number of hits for each failure mechanism. The
summation of all the hits equals 22,582, the same as the
total hits from the original data set recorded by the
LOCAN-AT. The vast majority of the hits (22,342) were
between 0 to 330 microseconds in duration. The 240
Mechanism 7 hits (1% of the entire data) had signal
durations randomly scattered between 331 to 20,000
microseconds. It is speculated that these very high
duration signals are characteristic of fiber pullouts since
they all occurred at or near specimen failure.
Table 1. Summary of the AE Parameter Characteristics for the Seven Failure Mechanisms.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Region</th>
<th>Duration [Microseconds]</th>
<th>Hits</th>
<th>Percent of total Hits</th>
<th>Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>0-55</td>
<td>9,878</td>
<td>43.7</td>
<td>23,731</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>56-82</td>
<td>2,804</td>
<td>12.4</td>
<td>22,002</td>
</tr>
<tr>
<td>3</td>
<td>III</td>
<td>83-104</td>
<td>2,002</td>
<td>8.9</td>
<td>24,784</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>105-141</td>
<td>2,808</td>
<td>12.4</td>
<td>50,415</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>142-179</td>
<td>2,374</td>
<td>10.5</td>
<td>58,121</td>
</tr>
<tr>
<td>6</td>
<td>II</td>
<td>180-330</td>
<td>2,476</td>
<td>11.0</td>
<td>81,258</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>&gt;331</td>
<td>240</td>
<td>1.1</td>
<td>23,607</td>
</tr>
</tbody>
</table>

Total Hits: 22,582

Table 2 summarizes the comparison between the amplitude distribution and the verification plots for the seven failure mechanisms. It can be seen that the peaks and the ranges of the amplitude distributions are the same as the peaks and the ranges of the counts versus amplitude plots for Mechanisms 1 through 6. The counts/hit ratios, calculated from the amplitude distribution data are at worst case only 2 counts/hit different from the peaks of the hits versus counts plots, further indicating that single failure mechanisms were isolated in each case. The
Verification plots were not applied to Mechanism 7 because its distribution was flat and would therefore provide no meaningful comparison.

Table 2. Summary of the Comparison Between the Amplitude Distribution and the Verification Plots for the Seven Failure Mechanisms.

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Amplitude Distribution</th>
<th>Verification Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>35-53</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>38-55</td>
</tr>
<tr>
<td>3</td>
<td>49</td>
<td>40-58</td>
</tr>
<tr>
<td>4</td>
<td>52</td>
<td>42-64</td>
</tr>
<tr>
<td>5</td>
<td>56</td>
<td>48-68</td>
</tr>
<tr>
<td>6</td>
<td>65</td>
<td>52-75</td>
</tr>
<tr>
<td>7</td>
<td>72</td>
<td>47-100</td>
</tr>
</tbody>
</table>

In two instances the verification graphs were used to show that more than one failure mechanism was present in the amplitude distribution. The peak and range of the amplitude distributions in both cases were considerably different.
than the peak and range of the counts versus amplitude plots. Furthermore, the calculated counts/hit values were different from the peaks of the hits versus counts plots.

It is of interest to note that the iterative search technique used in this work to isolate the failure mechanisms is different than the visual sorting technique of [8]. This is due to the difference in the amount of overlap encountered between the two cases. Here the overlap was much more extensive; therefore, visual sorting was not possible. Below is a summary, shown for convenience, of the differences between [8] and this work.

Ely and Hill [8]

Five layers of graphite/epoxy
Total system gain = 40 dB
Threshold = 50 dB
Total number of hits = 4725

Here:

Eight layers of fiberglass/epoxy
Total system gain = 60 dB
Threshold = 40 dB
Total number of hits = 22,582

It can be seen that the increase in the system gain, the decrease in the threshold, and the difference in the
material used resulted in 17,857 more hits being recorded, a 380% increase from [8] to here. Since there are significantly more processed hits in this work, the overlap is also significantly greater. This explains why there were not any discrete duration bands in the hits versus duration plot, i.e., the overlap was sufficiently pronounced that it hid or masked these intervals. Thus an iterative sort was required.
6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A fiberglass/epoxy composite tensile test specimen was loaded to failure while being monitored for its AE activity, the object being to isolate the flaw growth mechanisms in an effort to understand the failure processes. The resulting hits versus amplitude plot (amplitude distribution) was seen to be exponential in nature. Since several failure mechanisms were known to be present, the lack of any distinctly identifiable bands in the amplitude distribution indicated that there was considerable overlap between the various failure mechanisms.

After isolating the failure mechanisms, the following conclusions were made:

1. While Ely and Hill [8] were able to visually separate the various mechanisms by looking at the duration and rise-time distributions, here, because of extensive overlap in the AE data, an iterative approach was necessary.
2. Acoustic emission signal duration was the primary filter parameter. Iterations were made on various duration intervals until the proper intervals were found and each mechanism was isolated.

3. Two additional plots were necessary to verify that a single failure mechanism was present in the separated amplitude distributions: (1) the counts versus amplitude plot and (2) the hits versus counts plot. Here, similar shapes, peak locations, and counts/hit ratios between the three plots indicated the presence of a single failure mechanism. Conversely, dissimilar shapes, peak locations, or counts/hit ratios meant that more than one mechanism was present.

4. Seven failure mechanisms were eventually isolated from the original data set. The hits versus amplitude plot for Mechanism 1 was Weibullian in shape (skewed right) due to the cutoff provided by the 40 dB system threshold. Mechanisms 2 through 6 had normally distributed amplitude distributions, while the amplitude distribution for Mechanism 7 was flat (uniform).

6.2 RECOMMENDATIONS

It is recommended that a computerized routine be developed to perform the iterative search on the duration intervals.
Statistical data such as the mean, standard deviation, and skew could be calculated and compared between amplitude distributions and the counts versus amplitude plots. The chi-square goodness of fit test might also be used (for the normally distributed mechanisms) to select the best duration interval.

Another way to isolate the failure mechanisms is by using neural networks. A self organizing (unsupervised learning) network such as an Adaptive Resonance Theory 2 (ART 2) \cite{9} would be preferable because it does not require training data. This method classifies each signal according to the magnitude of its AE parameters. However, like the iterative search technique, classification performance in this type of network is limited by the amount of overlap. The overlap problem is less pronounced in the General Regression Neural Network (GRNN) \cite{10} where the regression surface is estimated from the training data presented to it. While this paradigm requires supervised learning, which is often viewed as a drawback, it has the advantages of one pass learning and accurate estimation of the regression surface with very few data points.

Other signal parameters might also be used to isolate the failure mechanisms. One such parameter is the frequency of the AE signal waveform. A broadband transducer would be required to sense this parameter, as well as a broadband
filter for both the preamplifier and the LOCAN-AT. A Transient Recorder Analyzer (TRA) board would also be needed to capture and perform frequency spectrum analysis on the AE waveform. If all seven failure mechanisms had different characteristic frequencies, then this would be a significant improvement over the iterative search technique. Even if there was only partial separation, it might still improve the performance of the latter mentioned technique.

Another means of separating the failure mechanisms is provided by making adjustments to the PDT and to the load rate. A test, similar to the one in this work, was conducted where the PDT and the load rate were reduced from 40 microseconds and 500 lbs/min to 30 microseconds and 100 lbs/min, respectively. By decreasing the PDT, the possibility of counting two signals as one is lowered. Moreover, the lowered load rate reduced the number of closely occurring signals. The resulting data distribution showed a reduction in the amount of overlap, particularly in the hits versus duration plot. Here the duration range was between 0 and 3,000 microseconds (rather than 0 to 20,000 microseconds) with many clearly distinguishable bands. Optimization of the PDT value would require further tensile tests coupled with the use of a TRA board in order to observe the rise-times of the actual waveforms. While the iterative search technique was successful in isolating
the various failure mechanisms, consideration of the above mentioned techniques is recommended for any future work.
7.0 REFERENCES


3. Frederick R. Kalloo, "Predicting Burst Pressures in Filament Wound Composite Pressure Vessels Using Acoustic Emission Data" (Master's Thesis, Embry-Riddle Aeronautical University, 1988), 3-4, 8, 8, 8, 8.


APPENDICES
APPENDIX A

ISOLATION OF MECHANISM 3

The amplitude distribution from Figure 17 was filtered from 83 to 104 microseconds in duration. The result was the hits versus amplitude plot of Figure 24. This represents a single predominant failure mechanism, normal in shape, which was confirmed by the verification plots. Labeled Mechanism 3, this amplitude band has its peak centered at 49 dB with a total of 2,002 hits and 24,784 counts, resulting in approximately 12 counts/hit. The plot extends from about 40 dB to 58 dB.

Figure 24. Hits Versus Amplitude (dB) Plot. Mechanism 3.
As seen from Figure 25, the peak of the counts versus amplitude plot is situated at 49 dB, the same as the distribution from Figure 24. As before, these two plots are very similar in shape.

![Counts Versus Amplitude (dB) Plot. Mechanism 3.](image)

Figure 25. Counts Versus Amplitude (dB) Plot. Mechanism 3.

Shown in Figure 26 is the hits versus counts plot, which is also seen to be a normal distribution. The peak is located at 13 counts, one count more than the counts/hit ratio of Figure 24. Once again, this is proof that only a single failure mechanism exists.
Figure 26. Hits Versus Counts Plot. Mechanism 3.
The next duration interval in the filter process was determined to be from 105 to 141 microseconds. The result is shown in Figure 27, the hits versus amplitude plot, which was separated from the Region III amplitude distribution (Figure 17). This amplitude band again appears to be normally distributed with a peak at 52 dB. Labeled Mechanism 4, this band ranged from 42 to 64 dB. There are 2,808 hits and 50,415 counts, yielding an average of 18 counts/hit.

Figure 27. Hits Versus Amplitude (dB) Plot. Mechanism 4.
As seen from the counts versus amplitude plot in Figure 28, the graph also has its peak located at 52 dB. This plot is very similar in shape to the plot of Figure 27.

Figure 28. Counts Versus Amplitude (dB) Plot. Mechanism 4.

Looking at Figure 29, the hits versus counts plot shows the graph with the peak located at 20 counts, only two counts/hit more than the amplitude graph from Figure 27. The verification plots therefore, once again, prove the presence of a single predominant failure mechanism.
Figure 29. Hits Versus Counts Plot.
Mechanism 4.
The remaining duration interval to be filtered was from 142 to 179 microseconds. The hits versus amplitude plot of Figure 30 was separated from the amplitude distribution of Figure 17. This amplitude band, labeled Mechanism 5, appears as a normally shaped curve with a peak located at 56 dB and a range from about 48 to 68 dB. Mechanism 5 contains 2,374 hits and 58,121 counts with a ratio of approximately 24 counts/hit.

Figure 30. Hits Versus Amplitude (dB) Plot. Mechanism 5.
To verify that the amplitude graph in Figure 30 is a single failure mechanism, the counts versus amplitude plot in Figure 31 is used. Again, note that this latter graph also has the peak at 56 dB and is similar in shape to the former.

The second verification graph is the hits versus counts plot shown in Figure 32. The shape of this curve can be represented by a normal distribution. Furthermore, the peak of this plot has its peak located at 26 counts, only 2 counts/hit more than the data of Figure 30.
Figure 32. Hits Versus Counts Plot. Mechanism 5.