Acoustic emission (AE) signals that are generated by different microscopic processes during flaw growth in graphite-epoxy specimens have measurably different characteristics. In particular, the amplitudes of the emissions and a parameter that describes their frequency spectral content seem to give the most information about the processes. These parameters have a range of values for a given process which can be described by certain types of analytical distribution functions. When several processes occur simultaneously during flaw growth, such as epoxy crazing, fiber fracture, fiber-matrix disbond and interlaminar cleavage, the distributions in the values of the AE parameters generally overlap so that identification of an individual AE signal as being caused by a particular process is not possible. However, statistical evaluation of the data for a few hundred events in terms of the analytical distributions, once the shape and modal value of these distributions are defined for each process, should provide a quantitative measure of the relative amounts of the various processes which occurred. Analyses of many data sets are required to develop confidence in the decomposed distributions as being descriptive of the individual processes. The ultimate purpose for this determination is to provide a description of the stage of flaw growth from the quantitative knowledge of the types and the amounts of the microscopic processes which occurred.

**INTRODUCTION**

The purpose of this study is to determine the current mechanical state of a composite by acoustic emission (AE) signature analysis and from that knowledge predict its remaining lifetime. Several laboratory specimen configurations were used in interpreting the signatures of the AE from the different fracture mechanisms, i.e. matrix fracture, fiber fracture, fiber-matrix disbond, fiber pullout, delamination. The data presented here are all from specimens with the triangular reduced cross-section shown in Poster 1.

**EXPERIMENTAL RESULTS**

Specimens with the triangular reduced cross-section were loaded in four-point bending so that the high stress region at the apex of the triangle was either in tension or compression. Some specimens had never been exposed to water and, others were fully saturated by soaking in 98°C water for several days. The relative amounts of the several possible fracture mechanisms were different under these four test conditions of otherwise identical specimens which permitted identification of the acoustic signature of those mechanisms. Posters 2 and 3 show some aspects of the acoustic signatures that can be obtained from among the 23 parameters collected for each AE event by the Acoustic Emission Multi-Parameter Analyzer (AEMPA) system. The most useful information in the acoustic signature was in the amplitudes and frequency spectra of the AE. For example in Poster 3 the trends in the frequency spectral amplitude ratio (the four scatter diagrams at the bottom) are quite different for the tension and compression tests. Here, the ratio of the peak amplitude at 56kHz to that at 56kHz for each AE event is plotted as a point at the time that the AE event occurred. For the tensile specimen this spectral amplitude ratio shows definite trends from about -5dB to -30dB to +30dB as different fracture mechanisms occurred during the loading history. The data for compressive failure, which is dominated by a single mechanism, do not show these trends. The amplitudes of the AE (the center scatter diagrams) also show that some of the mechanisms in tension are more energetic than those operating in compression.

**ANALYSIS OF RESULTS**

The scatter diagrams of Posters 2 and 3 are useful in showing trends in the acoustic signatures but cannot provide quantitative information about the amounts of the different fracture processes which occurred. This information can be obtained from the data by forming number distributions (cumulative or differential) of the events based on the values of one of the parameters of those events for various time periods throughout the tests. These distributions are then decomposed into their component distributions due to the various mechanisms which occurred during each time period.

**Decomposition of Amplitude Distributions** - Poster 4 shows the method and results of decomposing amplitude distributions for the four specimen conditions. It is realized that any such decomposition is not necessarily unique and that evidence for the reasonableness of the decomposition must be established. In modeling the shape of the amplitude distributions for the individual mechanisms it was realized that the power-law distribution function traditionally used to describe AE amplitude data was not appropriate, particularly when more than one mechanism occurs within the analysis time period. The power-law distribution function, \( N = N_0 (V/V_0)^{\lambda} \), implies an unbounded range of possible amplitudes for a given mechanism with an infinite number of events approaching zero amplitude.

The extreme value distribution function which was used in the present analysis, Poster 4, is identical to the power-law distribution for large amplitude values but includes the condition that if an increment of fracture occurs by a given mechanism, the amount of energy released has a minimum value related to the parameter \( V_0 \). Thus \( V_0 \) takes on a significance that it did not have in the
power-law description of the amplitude distribution, the modal value for the mechanism, while $N_0$ and $b$ are still the number of events due to that mechanism and the spread are the amplitudes (or energies) of those events.

The example on Poster 4 for the first 500 AE events detected from a wet tension specimen (Specimen #LSW-82) shows decomposition of the experimental amplitude distribution into cumulative distributions due to four mechanisms, each with their own values of $N_0$ and $V_0$. These values should not change unless the material properties change, e.g. wet vs. dry, but the number $N_0$ for each mechanism may change with time or loading conditions, and may be zero under some conditions.

Inspection of the table of decomposed distributions on Poster 4 shows this to be the case, particularly for the wet compression specimen (Specimen #LSW-83). At times during the test, the amplitude distribution showed that only one mechanism was operating and at other times either two or three. In each case these distributions have the same values of $b$ and $V_0$ that were found for identical specimens tested with the fibers at the apex of the triangle in tension although the values of $N_0$ are quite different. Decomposition of the amplitude distributions for specimens from the dry material result in somewhat different values of $b$ and $V_0$ as expected but are also less consistent. Part of the inconsistency may be due to a shallow layer of moisture absorbed during specimen fabrication although this can not explain all of it.

Decomposition of Spectral Type Distributions -
Unlike the amplitude distributions, there has been no prior history of spectral type distribution analysis and no theoretical development of the functional form of these distributions. While the modal value can reasonably be expected to be related to the specific type of mechanism from past studies, the shape of the distribution is thought to be related to details of the localized surroundings of the source and perhaps the orientation and size of the source. For example, the AE due to the tensile fracture of graphite fibers are expected to have similar frequency spectra modified slightly by the distribution and spacing of nearby unbroken fibers, the radial distribution in the thickness of the surrounding epoxy, the local interfacial bond strength between the fiber and the epoxy, the local stress distribution, the occurrence of a single fiber fracture or an avalanche of fractures, or a number of other localized differences. Analysis of these effects on the shape of the spectral parameter distribution was not attempted at this time. Decomposition of the experimental distributions was strictly empirical.

The first attempts to decompose the experimental spectral type distributions, such as the ones shown on Poster 5, were made with the arbitrary restriction that the shapes of the differential distribution peaks be symmetric about their modal values. It was found that in addition to the symmetrically shaped distributions centered at -16 dB, -4.5 dB and 5.5 dB, which are apparent (and are indicated) on the figure of Poster 5, curve fitting required distributions centered at -12 dB, -8.5 dB, -1.5 dB and occasionally a small peak at -23 dB. With these six (or seven) distributions, curve fitting to the experimental distributions, as in Poster 5, could be done with extremely small least squares residuals by just changing the number of events in each individual distribution for the different time periods of the test.

A very convincing conclusion about the validity of the decomposition of the spectral distributions would be if the number of decomposed distributions and the number of events in each of these distributions were in agreement with the decomposed amplitude distributions for the same time periods. This would indeed strongly indicate that separate mechanisms had been identified, each with its distinctive distribution of AE amplitude and frequency spectral characteristics. This correspondence has not yet been found, however, which leaves nagging questions about restricting the analysis to symmetric distributions and about over-fitting the experimental data. More analysis is required to answer these questions but the results so far are encouraging that this analysis will be fruitful.

CONCLUDING REMARKS
If AE signature analysis is successful in quantitatively assessing the amounts of the various source mechanisms which occurred during a small load increment, then, in those cases where the flaw grows by a well defined sequence of mechanistic steps, a description of the current state of the flaw can be made. Combining this information with stress analysis and fracture mechanics, as outlined on Poster 5, leads to the possibility for life prediction for a composite structure.

ACKNOWLEDGMENTS
This research was sponsored by the Center for Advanced NDE operated by the Science Center, Rockwell International, for the Advanced Research Projects Agency and the Air Force Materials Laboratory under Contract No. F3361-74-C-5180. The efforts of R. Govan in specimen fabrication and testing and Dr. R. K. Elsley and G. Lindberg in computer software development are gratefully acknowledged.
PURPOSES:

- DETERMINE THE CURRENT MECHANICAL STATE OF A COMPOSITE.
- PREDICT ITS REMAINING LIFETIME.

APPROACH:

- IDENTIFY CHARACTERISTIC ACOUSTIC EMISSION SIGNATURES USING MULTI-PARAMETER ANALYSIS.
- RELATE AE SIGNATURES TO SPECIFIC FLAW GROWTH MECHANISMS.
- COMBINE THIS INFORMATION WITH FRACTURE MECHANICS ANALYSIS TO PREDICT REMAINING LIFETIME.

EXPERIMENTAL METHOD:

- UNIDIRECTIONAL GRAPHITE-EPOXY COMPOSITE (AS/3501-5) TESTED DRY AND HYDROTHERMALLY AGED.
- FOUR-POINT BEND SPECIMENS WITH VARIOUS ORIENTATIONS AND GEOMETRIES TO ENHANCE SPECIFIC FRACTURE MECHANISMS.
- USE MULTI-PARAMETER ANALYZER AND MINICOMPUTER TO COLLECT AND ANALYSE ACOUSTIC EMISSION DATA.
- OBTAIN LOAD CURVES, VISUAL OBSERVATIONS AND SEM PHOTOGRAPHS TO IDENTIFY FRACTURE MECHANISMS.

SPECIMEN DESIGNATIONS, XY:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>FIBERS IN TENSION, CRACK GROWTH THRU THICKNESS</td>
</tr>
<tr>
<td>-LS</td>
<td>FIBERS IN COMPRESSION, CRACK GROWTH THRU THICKNESS</td>
</tr>
<tr>
<td>LT</td>
<td>FIBERS IN TENSION, CRACK GROWTH TRANSVERSE</td>
</tr>
<tr>
<td>-LT</td>
<td>FIBERS IN COMPRESSION, CRACK GROWTH TRANSVERSE</td>
</tr>
<tr>
<td>TS</td>
<td>TENSION NORMAL TO FIBERS, CRACK GROWTH THRU THICKNESS</td>
</tr>
<tr>
<td>TL</td>
<td>TENSION NORMAL TO FIBERS, CRACK GROWTH ALONG FIBERS</td>
</tr>
</tbody>
</table>

Poster 1
AE SIGNATURES

- LOAD - WHEN DRY, COMPRESSIVE STRENGTH IS GREATER.

- AE EVENT RATE - QUITE VARIABLE WITH TIME AND FROM SPECIMEN TO SPECIMEN. INDICATES DAMAGE RATE.

- AMPLITUDE – LARGER AMPLITUDE EMISSIONS DUE TO TENSILE FRACTURE OF FIBERS AND INTERPLY DELAMINATION WHEN TESTED IN TENSION.

- RATIO OF AMPLITUDE IN TWO FREQUENCY BANDS – THIS DEFINITION OF FREQUENCY SPECTRAL TYPE SUGGESTS:
  1. FIBER FRACTURE IS HIGHER FREQUENCY.
  2. DELAMINATION IS LOWER FREQUENCY.
  3. FIBER-MATRIX DEBONDING AND MATRIX FRACTURE ARE INTERMEDIATE FREQUENCY.
  4. DELAMINATION TENDS TO CREATE LARGER AMPLITUDE.
  5. MATRIX FRACTURE TENDS TO LOWER AMPLITUDE.
  6. FIBER FRACTURE IN COMPRESSION TENDS TO LOWER AMPLITUDE.
AE SIGNATURES

- Load when wet – Tensile strength is greater.

- AE event rate – Variable.

- Amplitude – Tends to lower amplitudes when wet and when tested in compression.

- Ratio of amplitude in two frequency bands – Similar observations wet or dry.
DECOMPOSITION OF AMPLITUDE DISTRIBUTIONS BY CURVE FITTING

The amplitude distribution for each acoustic emission mechanism (matrix fracture, fiber fracture, fiber-matrix disbond, etc.) was assumed to have the form of an extreme value function

\[ N = N_0 \left( \frac{1}{1 + e^{bV}} \right) \]

where \( N \) = cumulative distribution
\( V \) = peak voltage amplitude of the AE event
\( N_0 \) = number of AE events in the sample
\( b \) = shape of the distribution

V = modal amplitude value of the distribution

\[ V = \text{PEAK VOLTAGE AMPLITUDE DISTRIBUTION FOR EACH DECOMPOSITION OF AMPLITUDE DISTRIBUTIONS BY CURVE FITTING} \]

A check on the reasonableness of the decomposed distributions is that their shape and modal values remain constant throughout a test or change in a rational way. The number of events in each distribution will change during a test and will reveal the mix of the types of processes occurring.

changing material properties, e.g., by exposure of the composite to water, may change the modal values and shapes of the distributions.

### SUMMARY OF DECOMPOSED DISTRIBUTIONS

<table>
<thead>
<tr>
<th>EVENT NO.</th>
<th>MECHANISM 1</th>
<th>MECHANISM 2</th>
<th>MECHANISM 3</th>
<th>MECHANISM 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive</td>
<td>590 15.0</td>
<td>80 15.0</td>
<td>55 15.0</td>
<td>45 15.0</td>
</tr>
<tr>
<td>Compressive</td>
<td>555 20.0</td>
<td>20 20.0</td>
<td>55 20.0</td>
<td>45 20.0</td>
</tr>
<tr>
<td>Compressive</td>
<td>600 20.0</td>
<td>20 20.0</td>
<td>55 20.0</td>
<td>45 20.0</td>
</tr>
<tr>
<td>Tensile</td>
<td>560 20.0</td>
<td>20 20.0</td>
<td>55 20.0</td>
<td>45 20.0</td>
</tr>
</tbody>
</table>

Poster 4

DECOMPOSITION OF SPECTRAL TYPE DISTRIBUTIONS BY CURVE FITTING

Spectral type is defined as the ratio of the amplitude of an AE at low frequency to the amplitude at high frequency.

Number distributions of AE events based upon this spectral type parameter vary systematically during a specimen test as new fracture mechanisms occur.

Can these distributions be decomposed into component parts which can be associated with specific mechanisms? The first attempts were encouraging.

Will the component amplitude and spectral type distributions agree in assessing the amounts of the various AE sources?

This remains to be answered.

If AE signature analysis is successful in quantitatively assessing the amounts of the various source mechanisms which occurred during a small load increment.

Then, in those cases where the flaw grows by a well-defined sequence of mechanism steps, a description of the current state of the flaw can be made.

Combining this information with stress analysis and fracture mechanics leads to the possibility for life prediction for a composite structure.

Poster 5

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**LIFE PREDICTION USING AE SIGNATURE ANALYSIS**

<table>
<thead>
<tr>
<th>PROCEDURE</th>
<th>STEPS</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLY A REALISTIC PROOF LOAD TO A COMPONENT AND MONITOR ACOUSTIC EMISSION ACTIVITY.</td>
<td>DETERMINE SERVICE LOAD SPECTRUM. LOCATE ACTIVE REGIONS IF MORE THAN ONE. MINIMIZE FURTHER DAMAGE DUE TO PROOF LOAD.</td>
<td>PREVIOUS MAXIMUM SERVICE LOAD OR EXTENT OF PREVIOUS DAMAGE THROUGH KAISER EFFECT.</td>
</tr>
<tr>
<td>COLLECT A SAMPLE OF ACOUSTIC EMISSION EVENTS USING MULTIPARAMETER ANALYZER.</td>
<td>LOCALIZE DATA SET TO ONE ACTIVE REGION. OBTAIN SAMPLE FOR EACH ACTIVE REGION. ACCOUNT FOR GEOMETRICAL EFFECTS IN SIGNAL.</td>
<td>RELATIVE AMOUNT OF VARIOUS FRACTURE MECHANISMS WHICH OCCURRED THROUGH AMPLITUDE AND SPECTRAL TYPE DISTRIBUTIONS. LOAD LEVEL AT WHICH THEY OCCURRED.</td>
</tr>
<tr>
<td>CALCULATE STRESS DISTRIBUTION FOR EACH ACTIVE REGION AT PROOF LOAD.</td>
<td>ACCOUNT FOR COMPLEX STRUCTURE. ACCOUNT FOR PLY ORIENTATION. DETERMINE THROUGH THICKNESS DISTRIBUTION OF TENSILE, COMPRESSIVE AND SHEAR STRESSES.</td>
<td>MAGNITUDE AND THROUGH THICKNESS LOCATION OF MOST PROBABLE CRITICAL STRESS COMPONENT.</td>
</tr>
<tr>
<td>APPLY FRACTURE MECHANICS ANALYSIS.</td>
<td>ACCOUNT FOR MATERIALS PROPERTIES. ACCOUNT FOR PLY LAY-UP AND INTERACTIONS. DETERMINE FRACTURE CRITERION.</td>
<td>SEQUENCE OF MECHANISTIC STEPS IN THE GROWTH OF A FLAW TO CRITICALITY.</td>
</tr>
<tr>
<td>PREDICT FUTURE SERVICE CONDITIONS.</td>
<td>ESTIMATE LOAD SPECTRUM. ESTIMATE ENVIRONMENTAL EFFECTS.</td>
<td>FUTURE FLAW GROWTH RATE.</td>
</tr>
</tbody>
</table>

**CONCLUSIONS:**

*PRESENT MAXIMUM FLAW SIZE AND TYPE AT EACH ACTIVE LOCATION AS A FUNCTION OF ITS ASSUMED LOCATION THROUGH THE THICKNESS.

*PREDICTED SERVICE LIFE BASED ON PRESENT FLAW DESCRIPTION, SEQUENCE OF MECHANISTIC STEPS, AND FUTURE GROWTH RATE.*

Poster 6