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Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering

ACOUSTIC EMISSION IN COMPOSITES USING MPA

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The purpose of this study is to try to determine the current mechanical state of a composite specimen (or structure) and predict its remaining lifetime from the characteristics of the acoustic emission (AE) signals it emits under load. In previous studies of the characteristics of AE generated in graphite-epoxy composites, empirical observations were made relating the frequency content and the amplitude distributions of the AE signals to singular points on the loading curve of a specimen and to the composite's moisture content. Up to now, these relationships have been difficult to study systematically because of limitations in efficiently handling the large amount of data contained in the emission signals. With the Acoustic Emission Multi-Parameter Analyzer (AEMPA) (developed under a Science Center IR&D program), pertinent information is abstracted from each emission signal as it occurs during a test and is stored in compact digital form for subsequent data processing. Multi-parameter correlation and pattern recognition techniques among the 23 abstracted parameters are then used to identify distinct types of AE events, and various observations used to identify the microscopic mechanisms of flaw growth in the material which generate these different types. For those geometries and load conditions which product failure by a well-defined series of mechanistic steps (e.g., matrix crazing, fiber-matrix interface debonding, fiber fracture, interlaminar fracture), it may be possible to predict specimen failure by determining the relative amounts of the various mechanisms occurring at a given time in the life of the specimen from the AE signals. Progress along these lines using MPA is described.

INTRODUCTION

For several years broadband signature analysis of acoustic emissions from a variety of materials has been attempted, with some success, at the Science Center. This was done by recording the analog AE signals on a modified videocorder and then manually making time and frequency domain measurements on hundreds to thousands of the individual waveforms to try to extract features which could be related to specific AE generation mechanisms. To make this work easier and more quantitative, an Acoustic Emission Multi-Parameter Analyzer* was designed and constructed which makes a selected set of these measurements on each AE waveform as it occurs. These measured values are stored in the form of 32 bytes of digital data per event on a floppy disk for later computer processing. The first use of the AEMPA system is described here.

EXPERIMENTAL APPROACH

The objectives and experimental approach for this project are outlined on the first poster. As stated there, the ultimate objective is to be able to predict the remaining lifetime of a structural component from the signature of the AE generated during a proof load of that structure at any point in its service life. The success of the approach taken is predicated upon two essential conditions. The first is that the growth of the critical flaw proceeds by well-defined, sequential mechanistic steps. Substantial progress is being made in predicting this sequence for particular materials, geometries and loading conditions by the stress analysts. The second condition is that AE signatures for each of the critical mechanisms are unique and can be identified, which is the subject of the present study. Then, signature analysis can tell what mechanism, or statistical mix of mechanisms, are operating under the proof load and, therefore, at what point in the sequence of steps in its growth process the critical flaw is at that time. Knowing the expected future loading history, the remaining lifetime can then be estimated.

Four-point bend specimens with various orientations and geometries, as indicated in the first poster, were used to enhance specific fracture mechanisms. For the same purpose specimens were tested before exposure to moisture and after various degrees of hydrothermal aging. Identification of the mechanisms which occur in each case, although not complete at present, is being made from visual observations and loading curves obtained during the tests and SEM observations.

TEST RESULTS

Background. Prior work showed two characteristics of the AE signals which could be related to the processes which were occurring during fracture of a composite specimen. The shape of the AE amplitude distributions, shown in Poster 2, indicates that more than one process occurs simultaneously and each produces its own distribution of AE amplitudes. Further, the process which produces the lower amplitude emissions is enhanced when the specimen is exposed to moisture, and this shows up as a change in the initial slope of the amplitude distribution curve. Since the ultimate strength of the material is decreased by exposure to moisture, the initial slope of the amplitude distribution should be a measure of that decrease. The fracture loads for two sets of specimens of different orientations and various amounts of moisture content plotted against the initial slope of the AE amplitude distribution in Poster 2 show this relationship.

The second distinctive characteristic noted was that the frequency spectra of individual AE events were different and the different types occurred at definite points in the loading history.

*A more complete description of the AEMPA system can be found elsewhere in this report.

This suggested that the different spectral types were due to different mechanisms which occurred in the fracture process as the load increased. Examples of two different spectra are shown on Poster 2. Another comparison made in this figure is the appearance of the frequency spectral data when obtained by two methods. The AE signals from graphite-epoxy specimens were recorded on a modified videotape recorder and then during post-test analysis the two emission signals were analyzed by playing them back through a standard swept frequency spectrum analyzer (Hewlett Packard Model 141S/8553B/8552A) and an X-Y recording made of the spectrum, and through the AEMPA system. The same was done for a region of the electronic background noise immediately preceding each of the two emission bursts in order to establish the relative amplitude levels obtained by the two methods. Comparison of the discrete and continuous spectral data shows that the two spectral types are easily recognizable by either method. In fact a two point spectral analysis, say at 56 kHz and 560 kHz, would have been sufficient to separate the two types of emissions in this case.

The two characteristics of the AE signals shown in these figures, the amplitude distributions and the frequency spectral types, thus appear related to the mechanical state of the composite and might be used to define that state in a proof-test of a structure. Before that can be done, more quantitative relationships must be established between the particular mechanistic processes and the AE they produce. It should also be recognized that a particular process will produce AE having a statistical range of characteristics (e.g., amplitude) and that at any given time several different processes may be operative. Therefore, it must be demonstrated that the means for obtaining quantitative data on the AE characteristics is available and, further, that having these data the statistical mix of the various processes can be extracted from it.

In the past AE data acquisition systems commonly have measured one or two parameters of the emission signals and could display distributions of those parameters (e.g., number distribution with time, amplitude distribution). With the AEMPA system several measurements are made on each AE event as it occurs and 23 numbers are obtained which describe that event in terms of amplitude, timing, wave shape and frequency content. A description of these 23 parameters is shown on Poster 2. Each event also retains its individual identity which provides the possibility for extensive post-test statistical analyses on one or more parameters simultaneously and on the entire set or on sub-sets of the emission signals. Some results of such analyses for the composite specimens are shown in the following.

<u>AE Signatures in Composites</u>. Posters 3 and 4 show some results toward developing AE signatures for the various processes which occur during fracture of the composite specimens. Four specimen conditions are illustrated, all for the four-point bend specimen type of Poster 1 having the triangular reduced section. The conditions are that the graphite fibers (at the apex of the triangular section) are loaded in tension or compression and the specimens had never been exposed to moisture or are hydrothermally treated (in 95°C water) to attain a saturation water uptake. These four conditions result in emphasizing different fracture processes.

Each specimen was loaded through the elastic region into a region where fiber or matrix fracture or both occurred, further loaded until gross damage occurred from delamination (in tension) or fiber buckling (in compression), after which the specimens were unloaded. These various regions show up on the load curves and AE event rate curves as has often been seen in the past. Both of these parameters are difficult to interpret when only a small portion of the loading history of a specimen is available for analysis (such as in a proof-test situation). Their interpretation requires a comparison with values at earlier times in the specimen life to establish trends in the load bearing capacity or in the magnitude of the emission rate.

The time histories of the AE event amplitudes and frequency spectral types provide a fundamentally different type of information regarding the fracture processes which are occurring. These parameters contain information about the particular process which caused each event, presumably, and their interpretation requires no knowledge of what happened at some earlier time in the specimen history. If this is true then all that is required for interpretation is to obtain a large enough sample of AE events during a short time interval in the specimen life to define the statistical nature of the processes, and their quantitative mix if more than one process is operating.

Illustrative of this idea are the frequency spectral type plots at the bottom of Posters 3 and 4. Here a very simple measure of the spectral type is taken as the ratio of the peak amplitude of the AE in the 56 kHz filter band to that at 560 kHz. With reference to the spectra on Poster 2, a value of this ratio much greater than one indicates a low frequency type emission, about equal to one a broadband emission, and much less than one a high frequency type. For the compression specimens this ratio is about one for most of the emissions with a tendency for more high frequency events as the test progresses and more fibers fracture by buckling. The trends for the tensile specimens are quite different with the sudden occurrence of high frequency emissions coinciding with the onset of tensile fiber fracture, and then low frequency emissions occurring when delamination starts.

If the occurrence of these different spectral types truly correspond to occurrences of the different fracture processes, as is suggested by these data, then a sample of AE events at any time in the specimen history should define the processes going on independent of the past history. An example of this is shown at the bottom of Poster 5 where the four frames show number distributions of the "spectral type" parameter for four successive time periods for the wet tensile specimen data of Poster 4. Here it is seen how the distribution of AE events of different spectral types changes with time during the test. A quantitative decomposition of these distributions is suggested as being possible by the appearance of common peaks of differing amplitudes at -11, -4, and +5 dB. It should be pointed out here that the spectral type parameter used in these analyses is a very crude one and makes use of only two of the eight pieces of spectral data which are available. Other definitions of spectral type using all eight pieces of data are expected to be even more informative.

The two figures at the top of Poster 5 show the big difference in the amplitude distributions of the AE events for tensile and compressive specimen failure. The nearly straight line (power law) distribution for the compression specimen suggests that a single mechanism predominates in the AE generation while the shape of the distribution for the tensile specimen suggests that more than one mechanism was operating. As with the spectral type distributions, a quantitative decomposition of the amplitude distributions may be possible to give the relative amounts of each mechanism which occurred.

The plots of spectral type vs amplitude shown in Poster 5 are less informative than the others but do show that the lower frequency events tend to higher amplitude. This type event shows clearly in the scatter diagram for the compression specimen illustrated which was the only specimen of this type in which delamination is believed to have occurred.

The AE signatures shown in Posters 3, 4 and 5 represent the results of only a preliminary attempt with the Multi-Parameter Analysis capabilities that are now possible. In the fracture of graphite-epoxy composites, where several different mechanisms generally occur simultaneously, there appears to be a wealth of information contained in the AE signals which can be used to determine the current mechanical state of the specimen. Means for more effectively extracting that information from the data are under development.

LIFE PREDICTION

As stated earlier the ultimate objective of this study is to use AE signatures obtained from a proof-test to establish the current mechanical state of the structure and hence its expected remaining lifetime under a specified load history. The steps required for doing this are well defined and are outlined in Poster 6. For simple load conditions and geometries such as the laboratory bend specimens of this study, these procedures could now be followed to predict the remaining life of a specimen which had previously been loaded an unknown amount. This example, however, is a trivial case which does not present the complexities likely to be encountered in a structural component. The steps are the same though for a more complicated structure, with a key element being a description of the most critical flaw which is activated by the proof load. This description now seems possible at some points in the flaw growth history through the AE signature, and further refinements in the signature analysis are expected to improve that description.

PURPOSES:

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

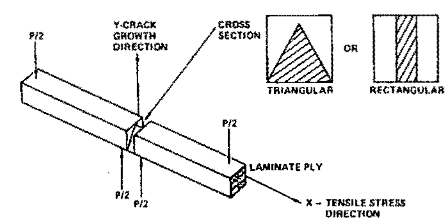
APPROACH:

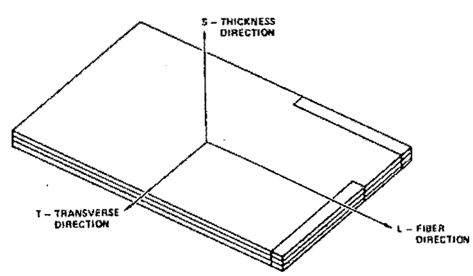
- **IDENTIFY CHARACTERISTIC ACOUSTIC EMISSION SIGNATURES USING MULTI-PARAMETER ANALYSIS.**
- **RELATE AE SIGNATURES TO SPECIFIC FLAW GROWTH MECHANISMS.**
- **COMBINE THIS INFORMATION WITH FRACTURE MECHANICS ANALYSIS TO PREDICT REMAINING LIFETIME.**

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.**

TEST SPECIMENS



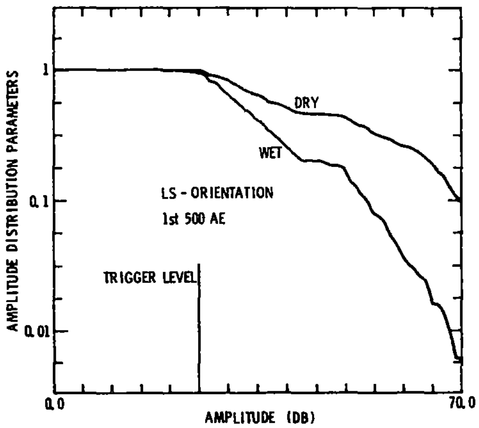


SPECIMEN DESIGNATIONS, XY:

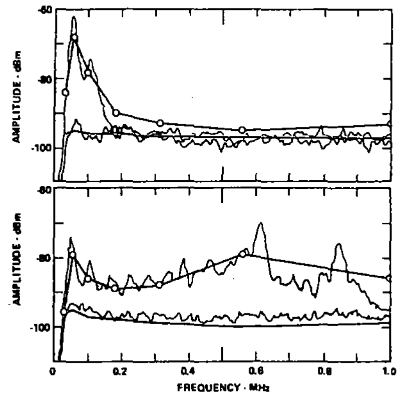
LS – FIBERS IN TENSION, CRACK GROWTH THRU THICKNESS
-LS – FIBERS IN COMPRESSION, CRACK GROWTH THRU THICKNESS
LT – FIBERS IN TENSION, CRACK GROWTH TRANSVERSE
-LT – FIBERS IN COMPRESSION, CRACK GROWTH TRANSVERSE
TS – TENSION NORMAL TO FIBERS, CRACK GROWTH THRU THICKNESS
TL – TENSION NORMAL TO FIBERS, CRACK GROWTH ALONG FIBERS

Poster 1

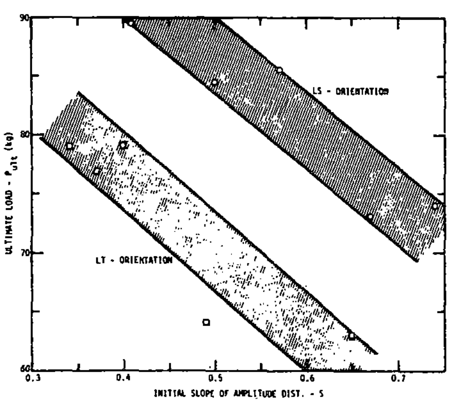
EFFECT OF WATER IN THE COMPOSITE ON THE INITIAL SLOPE OF THE AE AMPLITUDE DISTRIBUTION



DISTINCTIVE TYPES OF AE FREQUENCY SPECTRA OBTAINED BY ANALOG SPECTRUM ANALYZER AND AEMPA



RELATIONSHIP BETWEEN INITIAL SLOPE OF AMPLITUDE DISTRIBUTION AND ULTIMATE LOAD



PARAMETERS MEASURED FOR EACH AE EVENT BY AEMPA

	Measurement	Scale	0 DB REF*	Range
1.	Run Number	Hexadecimal		0 to 15
2.	Event Number	BCD Counts		0 to 8007
3.	Event Time	BCD Seconds		0 to 9999.999
4.	Analog Volts	BCD Volts		0 to 19.99
5.	Peak Amplitude	BCD DB	1 μV	0 to 99
6.	Energy Counts	BCD 200μV. μs/count		0 to 1,999,999
7.	Ring Down Count	BCD DB	1 count	0 to 118
8.	Event Duration	BCD DB	1 μs	0 to 118
9.	Event Rise Time	BCD DB	1 μs	0 to 118
10.	Filter Amplifier Overflow	1 bit Flag		0 or 1
11.	31.6 kHz Peak	BCD DB	10μV*	0 to 79
12.	56.2 kHz Peak	BCD DB	10μV*	0 to 79
13.	100 kHz Peak	BCD DB	10μV*	0 to 79
14.	177.8 kHz Peak	BCD DB	10μV*	0 to 79
15.	316 kHz Peak	BCD DB	10μV*	0 to 79
16.	562 kHz Peak	BCD DB	10μV*	0 to 79
17.	1 MHz Peak	BCD DB	10μV*	0 to 79
18.	1.778 MHz Peak	BCD DB	10μV*	0 to 79
19.	Biangulation Delay Time	BCD μs		0 to 99,999
20.	Load Gate Delay Time	BCD ms		0 to 99,999
21.	Filter Amplifier Gain	BCD DB	Unity	0 to 79
22.	Channel 1 Discriminator Gain	BCD DB	10 mV	0 to 79
23.	Channel 2 Discriminator Gain	BCD DB	10 mV	0 to 79
	2nd Channel Time Out	Decimal μs		10 to 99,990
	Load Start	Decimal ms		0 to 99,990
	Load Limit	Decimal ms		0 to 99,990
	Rate Delay	Decimal ms		0.1 to 9.9

*Varies with filter amplifier gain.

Poster 2

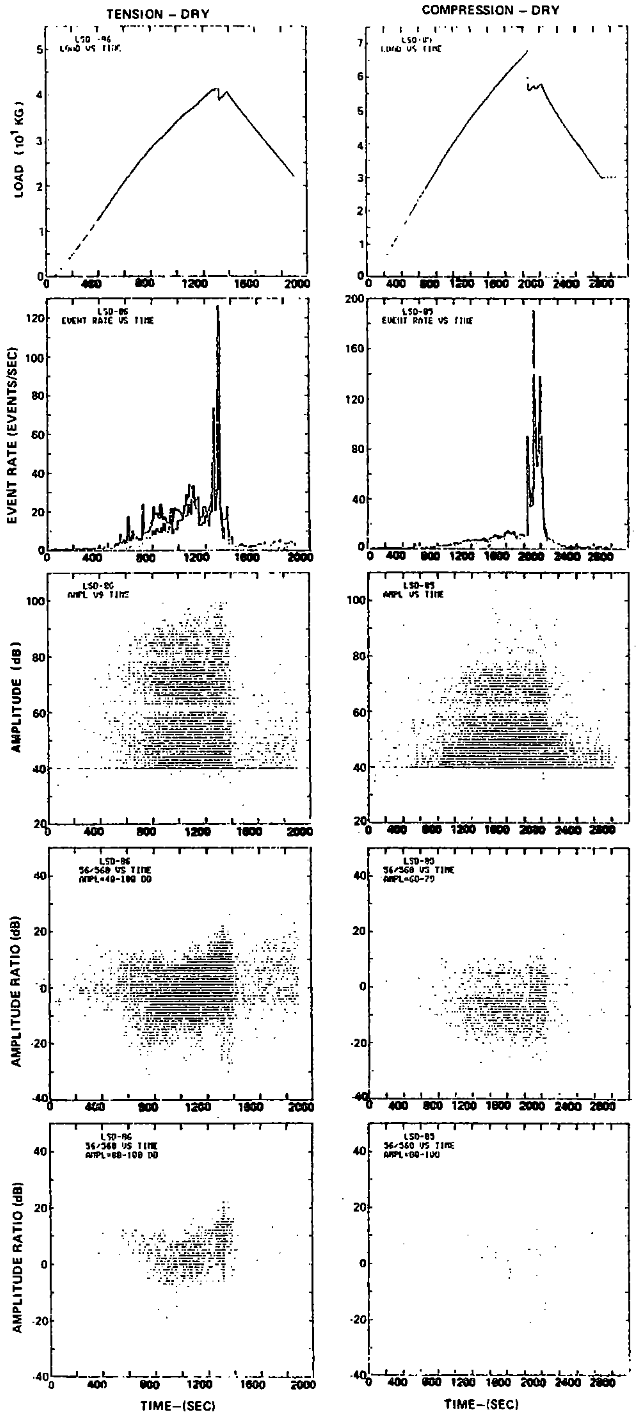
Characteristic acoustic emission parameters.

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

- LOAD – WHEN DRY, COMPRESSIVE STRENGTH IS GREATER.

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

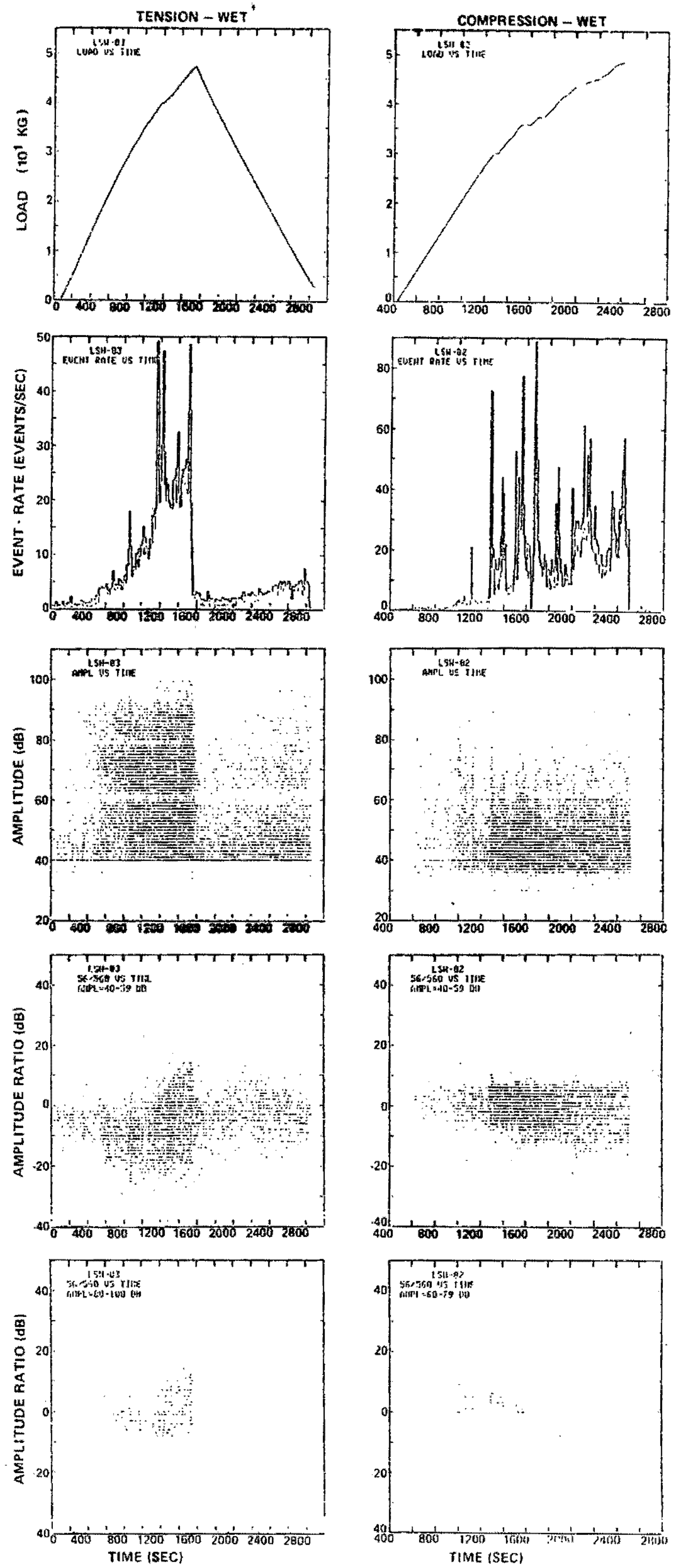
- RATIO OF AMPLITUDE IN TWO FREQUENCY BANDS – THIS DEFINITION OF FREQUENCY SPECTRAL TYPE SUGGESTS:
  1. FIBER FRACTURE IS HIGHER FREQUENCY.
  2. DELAMINATION IS LOWER FREQUENCY.
  3. FIBER-MATRIX DEBONDING AND MATRIX FRACTURE ARE INTERMEDIATE FREQUENCY.
  4. DELAMINATION TENDS TO CREATE LARGER AMPLITUDE.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



Poster 3

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

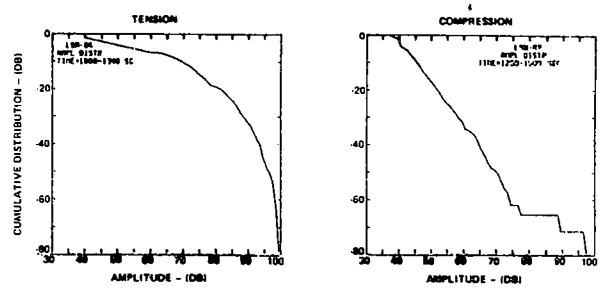


Poster 4

AE signatures

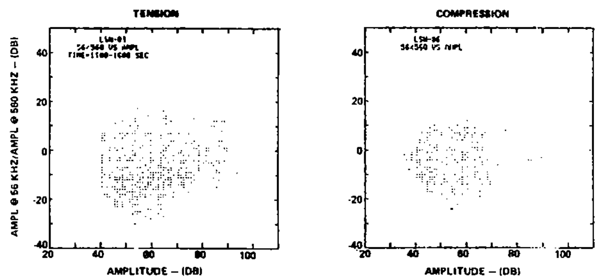
•AMPLITUDE DISTRIBUTION – A MARKED DIFFERENCE DUE TO THE MECHANISMS WHICH OCCUR IN TENSION AND IN COMPRESSION IS SEEN IN THE AMPLITUDES OF THE AE.

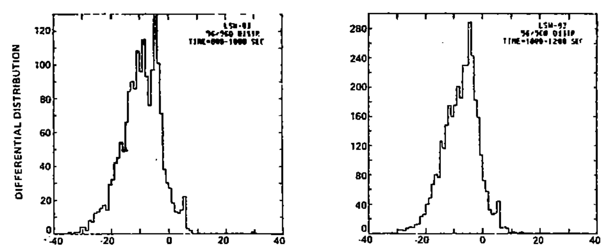
QUANTITATIVE DECOMPOSITION OF THESE DISTRIBUTIONS MAY BE POSSIBLE TO GIVE THE RELATIVE AMOUNTS OF EACH MECHANISM WHICH OCCURRED.



•SPECTRAL TYPE VS AMPLITUDE – THERE IS A TENDENCY FOR THE LOWER FREQUENCY EVENTS TO BE HIGHER AMPLITUDE.

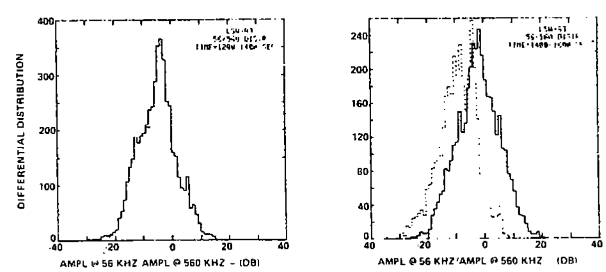
THE COMPRESSION TEST RESULTS ARE ATYPICAL BECAUSE OF LOW FREQUENCY, HIGH AMPLITUDE EVENTS WHICH SUGGEST THAT DELAMINATION OCCURRED IN THIS SPECIMEN.





•SPECTRAL TYPE DISTRIBUTION – DISTRIBUTIONS CENTERED AT SPECTRAL AMPLITUDE RATIOS OF -11, -4 AND +5 DB CHANGE IN RELATIVE NUMBER OF EVENTS WITH TIME.

QUANTITATIVE DECOMPOSITION OF THESE DISTRIBUTIONS MAY BE POSSIBLE TO GIVE THE RELATIVE AMOUNTS OF EACH MECHANISM WHICH OCCURRED.



Poster 5

AE signatures

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

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

Life prediction using AE signature analysis.