

WAVEFORM ANALYSIS OF AE IN COMPOSITES

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ABSTRACT

Advanced, waveform based acoustic emission (AE) techniques have been developed to evaluate damage mechanisms in the testing of composite materials. This approach, more recently referred to as Modal AE, provides an enhanced capability to discriminate and eliminate noise signals from those generated by damage mechanisms. Much more precise source location can also be obtained in comparison to conventional, threshold crossing arrival time determination techniques. Two successful examples of the application of Modal AE are presented in this work. In the first, the initiation of transverse matrix cracking in cross-ply, tensile coupons was monitored. In these tests, it was documented that the same source mechanism, matrix cracking, can produce widely different AE signal amplitudes dependent on laminate stacking sequence and thickness. These results, taken together with well known propagation effects of attenuation and dispersion of AE signals in composite laminates, cast further doubt on the validity of simple amplitude or amplitude distribution analysis for AE source determination. For the second example, delamination propagation in composite ring specimens was monitored. Pressurization of these composite rings is used to simulate the stresses in a composite rocket motor case. AE signals from delamination propagation were characterized by large amplitude flexural plate mode components which have long signal durations because of the large dispersion of this mode.

INTRODUCTION

The capabilities of AE testing in composite materials research have been significantly improved by several recent advances. These include the development of digital, waveform based, acquisition instrumentation with sufficient memory and acquisition rates for AE testing. Another important development has been the improvements in high fidelity, high sensitivity, broadband sensors. However, one of the most important advances has been the increased understanding of the nature of AE signal propagation as guided acoustic modes in common testing specimen geometries such as thin plates and coupons [1-3]. The analysis of guided mode AE signals has been designated Modal AE. However, the term Modal AE can be extended to include the analysis of bulk wave propagation as well. The major premise of this analysis approach is that the source motion affects the modes that are propagated in the AE signal. Thus, analysis of these modes in the digitized waveform can be used in conjunction with an understanding of wave propagation in the specimen geometry of interest, to determine the type of source and/or to discriminate and eliminate noise [4-5]. Understanding of the modes of propagation and their dispersive nature, combined with digital waveform acquisition and analysis, has also led to significantly improved AE source location accuracy [6].

Two sets of Modal AE measurements are presented herein. The first is an example of a successful application in composite materials research to monitor the initiation of transverse matrix cracking in cross-ply graphite/epoxy coupons. In these experiments, noise signals created by damage in the grip region were differentiated from crack signals by waveform analysis. The signals from matrix cracks contained a higher amplitude extensional plate mode component with little or no flexural mode. The grip damage signals contained significant flexural mode components.

The second application of Modal AE presented was the detection of the initiation of, and monitoring the growth of, delaminations in composite rocket motor case specimens. In these tests, rings of composite materials were pressurized in a special fixture to simulate stresses in a composite rocket motor case. Specimens with no damage, as well as those with intentional processing variations and/or damage were tested to simulate manufacturing flaws or handling damage that might exist in real motor cases. AE was able to successfully detect the onset of delaminations. Additionally, it was demonstrated that the growth of the delaminations could be tracked with AE in-situ. This was confirmed in one specimen by repeatedly stopping the pressurization test and measuring the extent of the delamination with ultrasonic methods. The delamination size as measured with ultrasonics was in good agreement with the AE results.

MODAL AE

A number of early AE studies [7-10] made passing mention of the propagation of AE waves as guided acoustic modes in practical testing geometries such as coupons, plates, shells, pipes, and rods. However, these works offered little as to the importance of these modes on the interpretation and analysis of AE with respect to source location accuracy and identification of source mechanisms. In fact, Pollock [11] raised these same questions in a review paper on critical problems for research in AE. In more recent work [1-3], the effects of guided wave propagation on the interpretation of AE in plates were demonstrated. It was pointed out that in thin plates and coupons, the two observed modes of propagation in AE signals are the extensional and flexural plate modes (lowest orders symmetric and antisymmetric Lamb modes respectively). The predominant particle displacement for the extensional mode is in the plane of the plate. The largest component of the flexural mode particle displacement is out of the plane of the plate. A source motion with predominantly in-plane components and symmetric about the midplane generates AE signals with large extensional mode components. Examples of such a source motion include fatigue cracking in metals and matrix cracking in the center plies of a composite laminate. Out of plane source motion such as delamination or impact damage produces AE signals with large flexural mode components. This discovery led to a waveform analysis method to identify sources and discriminate noise signals and is the basis for the Modal AE technique.

The extensional mode propagates with a faster velocity and suffers little dispersion over the frequency range observed in most AE experiments. It typically contains higher frequency components than the flexural mode. The flexural mode, however, propagates with a slower velocity and is highly dispersive with the higher frequencies traveling at higher velocities. A typical waveform detected in a composite plate with a broad band sensor identifying these two modes is shown in Fig. 1. The source of this signal was a simulated AE event caused by a pencil lead fracture (Hsu-Neilsen source) on the surface of the composite plate.

TRANSVERSE MATRIX CRACK INITIATION IN CROSS-PLY LAMINATES

The initiation and progression of transverse matrix cracking in composite materials has been, and remains, a subject of considerable interest and importance. A vast amount of literature on the experimental detection of matrix cracks is available, of which, a small sampling is reviewed in [5]. The improved source location accuracy and enhanced noise discrimination capabilities of the Modal AE technique were demonstrated in this study of the transverse matrix crack initiation in cross-ply laminates of different stacking sequences. This work improved upon a recent similar study [12] in which only a single cross-ply laminate was tested.

Tensile coupon specimens (2.54 cm. wide by 27.94 cm. long) of AS4/3502 graphite/epoxy composite material were loaded in tension under stroke control (0.127 mm/minute). As grip noise was eliminated by waveform analysis, specimen end tabs were not used in these tests. Specimens from six different cross-

ply laminates were tested. The stacking sequences were $[0_n, 90_n, 0_n]$ where n ranged from one to six. Thus, the samples varied in thickness from 3 to 18 plies.

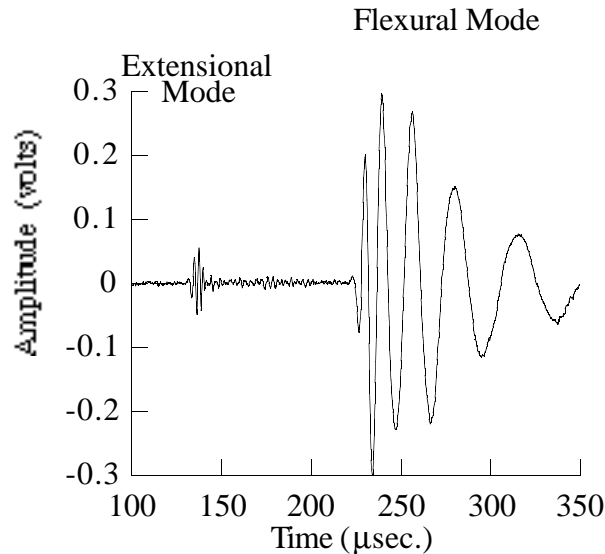


Fig. 1 Simulated AE signal in composite plate identifying extensional and flexural plate modes.

Broadband, high fidelity sensors were used to detect the waveforms. Rather than a single sensor at either end of the specimen as in many previous works, four sensors were used. At either end of the nominally 152 mm. specimen gage length, a pair of sensors were positioned. The outer edge of each 6.35 mm diameter sensor was aligned with the edge of the specimen. A diagram of a specimen showing the sensor positions and the grip regions is shown in Fig. 2. The motivation for this sensor array arrangement was the determination of the initiation site of the crack. Not only could the linear location along the length of the specimen be determined, but lateral location information was also obtained. The maximum digitization sampling frequency (25 MHz) of the digital AE acquisition and analysis system was used to provide the most accurate location results. Location was performed, post-test, using manual, cursor based phase point matching on the extensional mode for arrival time determination. The extensional mode velocities used for the location analysis were measured prior to testing using simulated AE sources.

After detection, the signals were amplified 20 dB by wide band preamps. It was determined during the tests that the signal amplitudes were a function of the 90 degree layer thickness, so additional system gain was varied to maintain the signal within the limited dynamic range of the 8 bit vertical resolution of the digitizer. Thicker specimens generated signals of larger amplitude. The additional system gain ranged from as little as 6 dB for the thickest specimen to 18 dB for the nine ply specimen ($n = 3$). For the three and six ply laminates ($n = 1$ and 2), the signal amplitudes were significantly smaller as will be discussed below. For these, the preamp gain was increased to 40 dB and the system gain was set as high as 18 dB in attempts to capture the much smaller amplitude signals.

After detection of one or more transverse matrix crack AE signals, the specimen was removed from the test machine. One edge of the specimen, which had been polished prior to testing, was examined under an optical microscope. The specimen was mounted on an x-y translation stage to allow measurement of crack locations for comparison with the AE data. Backscatter ultrasonic scans were taken to further confirm the crack locations and to provide information about the lateral extent of the cracks. This method also confirmed that no cracks existed which were not detected at the one polished edge. In some cases, penetrant enhanced radiography was also used as was destructive sectioning and microscopy.

Extraneous noise signals were eliminated by post test analysis of the waveforms. Typical waveforms from both a crack source and a noise source are shown in Fig. 3. Because of the multiple reflections of the signals across the narrow width of the coupons, the signals are more complicated than those presented in Fig. 1 which were detected in a large plate. However, the high frequency extensional mode is clear in the crack signal. A small extensional mode component is observed in the noise signal followed by a much larger, low frequency, dispersive flexural mode signal. The source of the noise signals is believed to be grip damage or specimen slippage in the grips as all of the noise signals located outside the specimen gage length in the grip regions.

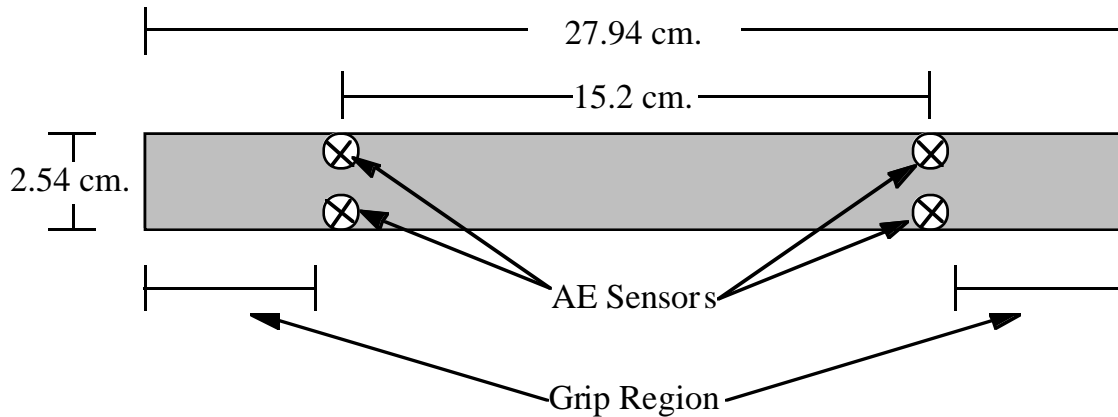


Fig. 2 Diagram of specimen showing grip region and position of AE sensors

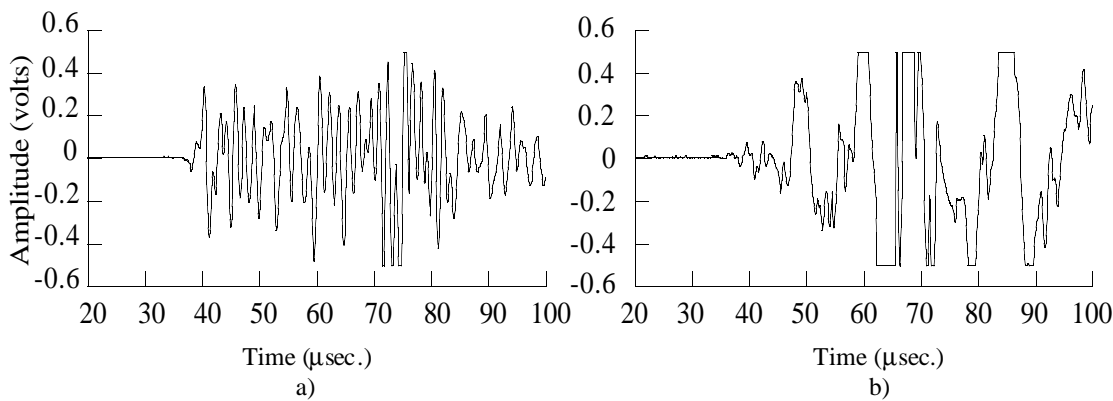
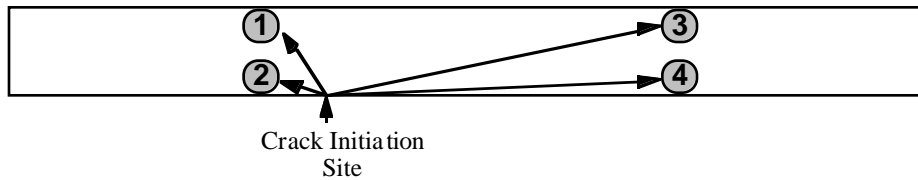
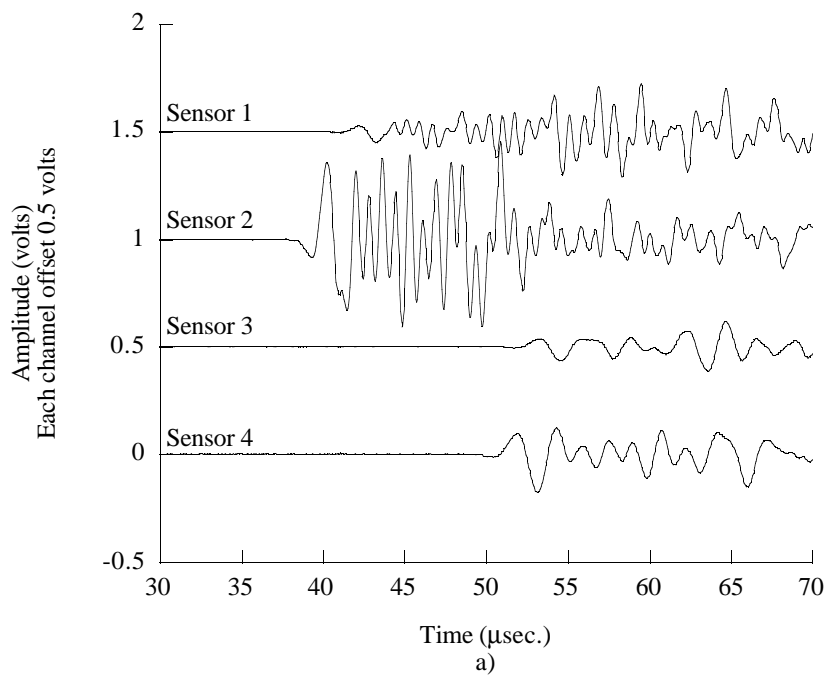


Fig. 3 Typical signals caused by a) transverse matrix crack and b) grip slippage or damage

For the laminates with $n = 3$ or larger, there was an exact one-to-one correlation between AE crack signals and cracks confirmed with microscopy. Backscatter ultrasonics indicated that all of these cracks extended across the full width of the specimen and that none were present which were not observed by microscopy of the polished edge. Destructive sectioning and microscopy of a few of these cracks also confirmed this result. The fact that only a single AE signal was detected for each crack indicates that the cracks immediately propagated across the width of the specimen.

Location analysis of the four sensor array data showed that all cracks initiated along one of the specimen edges. A typical four channel set of waveforms from a matrix crack signal is shown in Fig. 4 along with a diagram indicating the sensor positions and the crack location. The time delay between the

sensor pairs associated with the crack initiation site being located along the edge is clearly seen. Furthermore, differences in signal amplitudes between the sensors within a pair are the result of the increased attenuation from propagation across the specimen width. The differences in signal amplitudes and frequency content for signals detected at opposite ends of the specimen and thus different distances of propagation distances should also be noted. These differences, which are caused by attenuation and dispersion, can have significant effects on location accuracy in threshold based arrival time AE measurement systems. Conventional amplitude distribution analysis is also affected by this attenuation. Excellent crack location accuracy along the length of the specimens was also obtained from the AE data as compared to microscopy measurements. The most accurate linear location was obtained by using the two sensors on the same edge as the crack initiation site. The average of the absolute value of the difference in crack locations from AE and microscopy was 3.2 mm for a nominal sensor gage length of 152 mm.



b)

Fig. 4 a) Set of four channel waveforms indicating crack initiation along the specimen edge and b) diagram showing sensor positions, crack initiation site, and rays of direct propagation for the AE signal.

For the thin laminates ($n = 1$ or 2), the AE signals from cracks were not always successfully detected and the signals detected were significantly smaller in amplitude. Ultrasonic backscatter scans and destructive sectioning microscopy analysis showed that the cracks, which were visible at the specimen edge, did not extend into the interior of the specimen. Thus, the cracks were again initiating along the edge, but not progressing immediately across the specimen. This difference in crack initiation and growth behavior explains the much smaller amplitude signals and the difficulty in detecting these cracks.

DELAMINATION DETECTION IN ROCKET MOTOR CASE RINGS

Acoustic emission was used to monitor the initiation and growth of delaminations in 50.8 cm diameter IM7/HBRF 55A composite ring specimens. The rings had a laminate stacking sequence as shown in Fig. 5. Both undamaged rings as well as rings with manufacturing variations and intentional damage were tested in a special pressurization fixture. This fixture consisted of large steel plates which were bolted together on the top and bottom of the ring, which was then pressurized by a large rubber bladder. These testing conditions allow the simulation of the mechanical stresses obtained in a cross section of a composite rocket motor case.

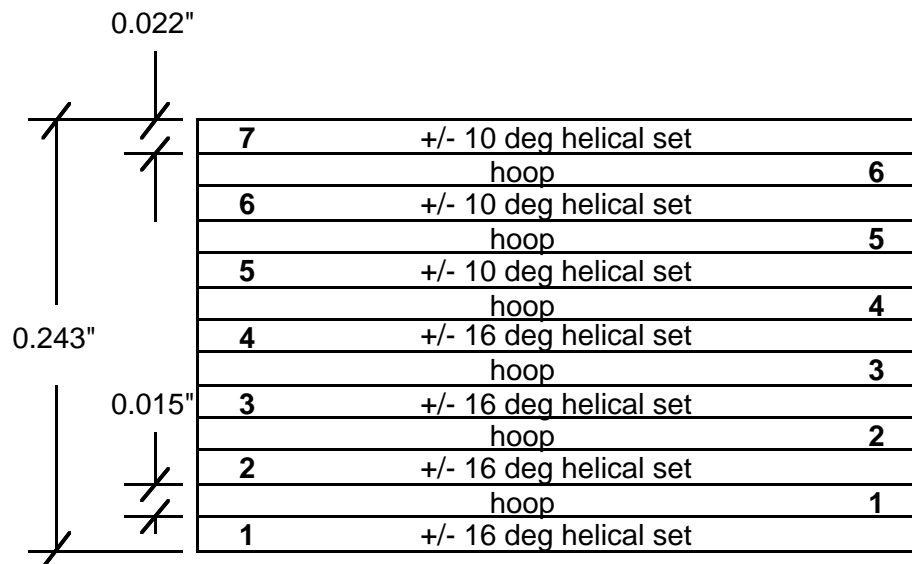


Fig. 5 Laminate stacking sequence in composite ring specimens.

Eight broadband AE sensors were attached around the circumference of the ring. A preamplifier provided 20 dB of initial gain at the sensor. An additional 18 dB of gain was provided in the signal conditioning module. A newer model digital waveform acquisition system was used which provided 12 bit vertical resolution A/D conversion. For these experiments, a 5 MHz sampling frequency was used.

Unlike transverse matrix cracking within the center laminate of a cross-ply composite, AE signals from delamination contain a large amplitude flexural mode component [13]. The dispersion of this mode of propagation leads to signals with long durations. This correlation between long duration AE signals and delamination source mechanisms has been previously reported based on conventional, parameter based, AE measurements [14]. In addition to large flexural components, the signals from delaminations in this study also had large amplitudes. The combination of large amplitude, long duration resulted in signals of large energy. Fig. 6 shows three typical signals from this testing. The upper two signals are associated with delamination and contain large amplitude flexural mode components. They also have large energy values as measured by the integration of the square of the voltage with respect to time. It is noted that both the amplitude of both of these signals exceeded the dynamic range of the A/D and were clipped. Thus, the

energy values are not representative of the actual signal which would have yielded a larger value. However, the calculated values are considerably larger than that of the lower signal in this figure which was most likely caused by matrix cracking. It is noted that care must be taken in comparing a parameter such as energy calculated from a digitized waveform. This is because the digitized waveform does not contain the entire signal, rather only a snapshot of a portion thereof. Thus, the energy does not represent the entire energy of the signal. If the triggering conditions are different, the waveform will be shifted in the digitization window and may provide a somewhat different value of energy. However, for these tests, the signal energy was merely used as a method for grouping the signals. Very large energy signals, which contained large flexural modes, were correlated to delamination growth by location analysis. The smaller energy signals were located at various positions over the entire ring specimen, while large energy signals occurred only at delaminations.

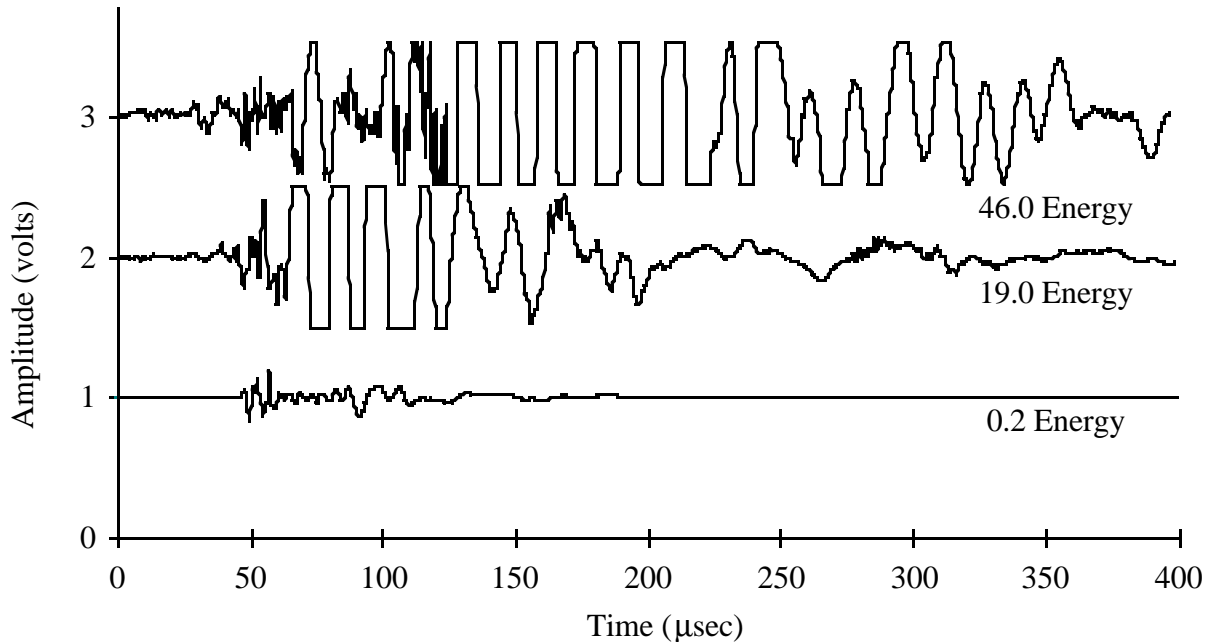


Fig. 6 Typical signals from composite ring pressurization test. Upper two signals with large energy values and large flexural mode components correlate with delamination growth. Signals such as the lower trace with low energy and little flexural mode occurred around the specimen and are most likely related to matrix cracking.

Fig. 7a shows the location results for AE signals as a function of pressure for a composite ring specimen. In this sample, a hole was drilled through a single lamina to initiate delamination. A micrograph of the hole and resulting delamination from such a specimen is shown in Fig. 7b. The location results show the occurrence of low energy signals at widespread locations over a wide range of pressures. However, higher energy signals are only located near the hole site and at higher pressures at which the delamination initiated and propagated. As the pressure increased and the delamination propagated, a widening of the locations of these high energy signal locations was observed. This is reflected in Fig. 7b and corresponds to the increased length of delamination. For one specimen, the test was stopped at a number of pressure intervals and unloaded so that the position and extent of delamination could be mapped with an ultrasonic inspection. The AE location results were found to be in good agreement with the ultrasonic inspection results. An increased density of the lower energy signals was also observed at higher pressure at locations corresponding to the delamination. It is suspected that these were caused by matrix cracking and/or micro delamination events associated with the macroscopic delamination growth.

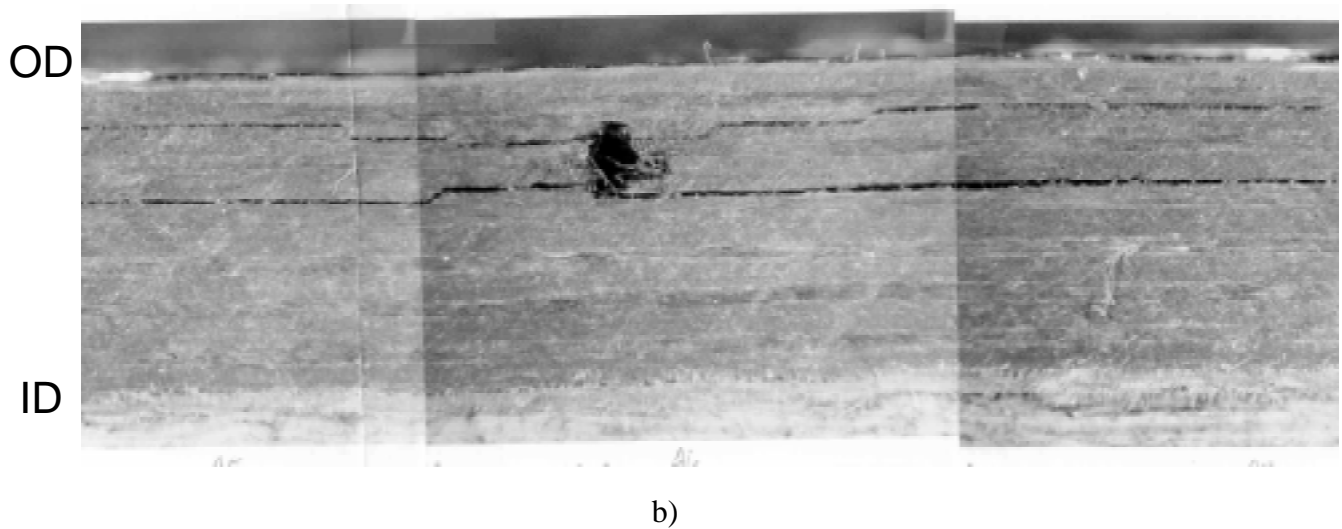
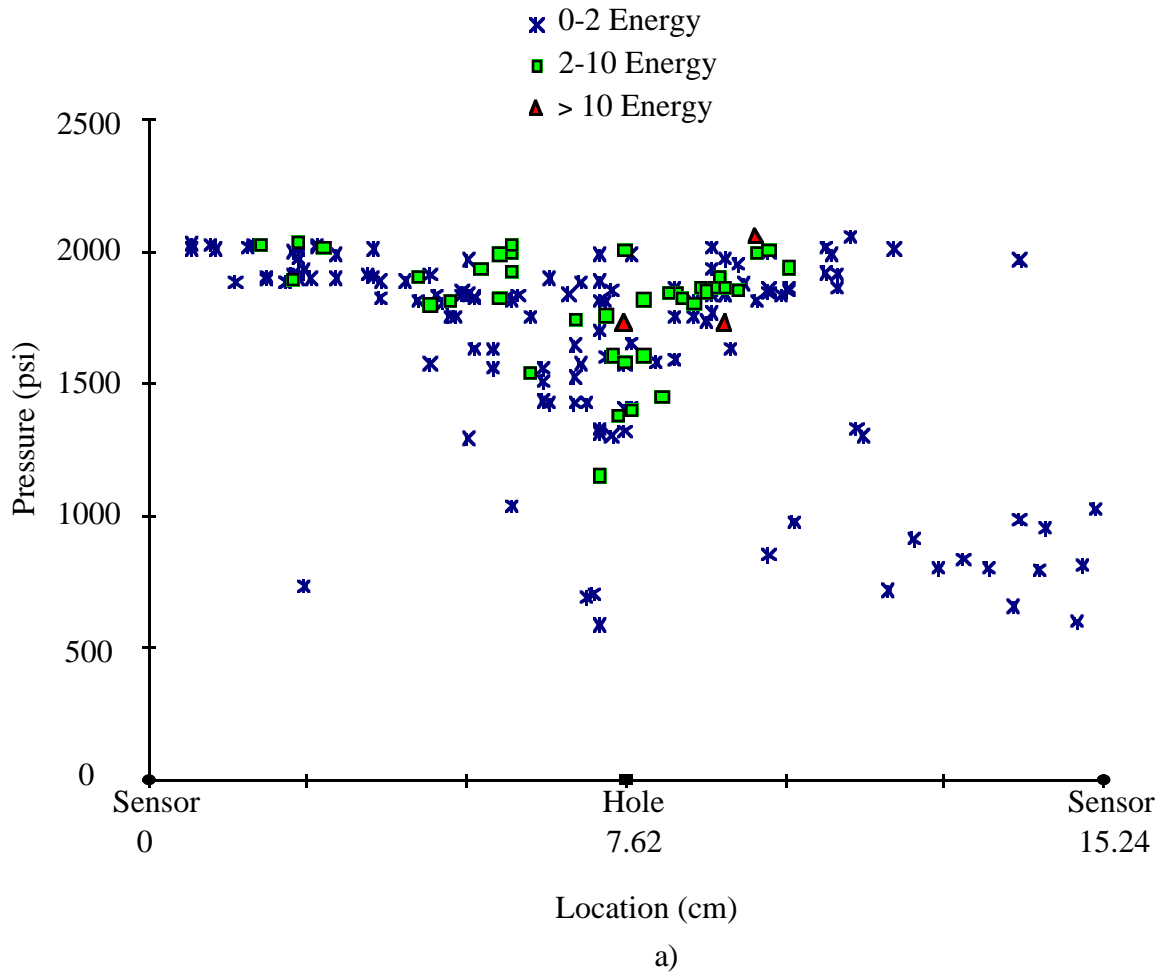


Fig. 7 a) AE location results as a function of pressure for composite ring specimen with a drilled hole to initiate delamination, and b) micrograph of specimen showing hole and resultant delamination growth.

SUMMARY AND CONCLUSIONS

The results of these two tests demonstrate the potential of Modal AE. The successful detection of transverse matrix cracking in cross-ply graphite/epoxy composites with thick 90 degree layers shows the capability to identify a particular source mechanism and differentiate noise signals. Excellent source location results were obtained. Not only was the position of the cracks along the specimen length determined and in excellent agreement with microscopy results, but the lateral position of the crack initiation site was also determined. In these coupons, all cracks initiated along one of the specimen edges.

The difficulty in detecting matrix cracking in similar specimens with thin 90 degree layers illustrates a couple of points. First, the same source mechanism can produce AE signals with significantly different amplitudes. In this case, the amplitude was dependent on the thickness of 90 degree plies and the length of crack advance. A similar result might also be expected for other source mechanisms. In a real structure, it is anticipated that the length of advance for a given crack or delamination might vary considerably dependent on local stress conditions. Furthermore, damage will occur in different layers which might have different thicknesses. These factors cast considerable doubts on the capabilities of conventional amplitude distribution analyses for differentiating source mechanisms. This is especially true in light of the considerable effects of attenuation in composite materials.

The second point involves the generalization of the Modal AE technique. Although the technique was used in these two sets of tests to differentiate signals from matrix cracks and delaminations, considerable research advances are required before the technique is able to differentiate a number of source mechanisms in arbitrary materials, laminates, and or specimen geometries. Currently, AE signals in each new type of specimen must be carefully characterized and studied. Furthermore, at least for initial specimens, other techniques such as microscopy should be used to confirm the ability to use AE to identify a particular source mechanism in a particular material/laminate/geometry. Developments in modeling AE wave propagation will aid in expanding the applicability of Modal AE by providing insight into the effects of different source mechanisms on observed AE signals.

The composite ring specimen tests demonstrate that delamination growth can be monitored with Modal AE. Delamination sources produce signals with large flexural plate mode components. The correlation between delamination sources and long duration AE events has been noted in prior research and it is commonly held that this might be related to a difference in source rise time or duration. However, the dispersion of this propagation mode is more likely the cause for the long duration events as it causes the signal to distort and lengthen in time as it propagates over longer distances.

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