Characterization of Acoustic Emission Signals and Application to Composite Structures Monitoring

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The objectives of this study were first, to identify characteristics of the acoustic emission signals from graphite-epoxy composites which could be related to the various fracture mechanisms, and second, to determine how these are related to the history of the flaw growth and to the degree of degradation of the strength of the composites due to moisture.

The fracture behavior of the composite specimens was very erratic as was the acoustic emission magnitude. As a result, it was very difficult to perform a systematic study to relate acoustic emission characteristics with any specific fracture mechanism such as fiber fracture, matrix fracture, or fiber pullout.

Another difficulty was that there were only very subtle differences in the acoustic emission characteristics between the unaged material and the fully aged or moisture degraded material, although there were big differences in the mechanical properties of the composites due to aging.

We have made some progress, however, and I would like to present some of the results now in the context of how they might apply to monitoring a structure in a proof loading situation.

We looked at three materials. These are the same materials that Dave Kaelble and Paul Dynes looked at during last year's and this year's program. They were all unidirectional graphite-epoxy fiber composites made into laminate sheets about a quarter inch thick, and were chosen to have different degrees of moisture susceptibility.

We tried quite a few different specimen geometries; however, most of the work was done with three-point bend specimens. These bend specimens were two and a half inch long bars having about a quarter inch square cross section. Side grooves were cut into each side of the bar at the mid-length, leaving about a 90 mil wide web down which the crack propagated.

With this geometrical orientation in mind, the left-hand picture of Fig. 1 shows the fracture surface of one of these bend specimens. Cracks started at the top at the maximum tensile stress position on the specimen and proceeded down through the 90 mil wide web.

On the right of Fig. 1 is an artist's drawing of that fracture surface. The main features are that there are very smooth regions and very rough regions of fracture. Through the load diagrams we have established that fast fracture produces a smooth surface and very slow, semi-stable crack growth produces a very rough surface.

Figure 1. Combination of observed load and acoustic emission data with implications of the appearance of the fracture surface to arrive at crack growth parameters.

From this observation, we can make correlations with the acoustic emission data and can calculate certain parameters. For example, after abrupt load drops or certain other key features on the loading curve, and knowing what the crack length is at that time, we can calculate the approximate stress intensity factor. Some of these values are indicated on Fig. 1 where you can see a range of values at different times in the load history. I must emphasize that these are only approximate because of the complex geometry of the specimen, but are sufficient for the purpose of comparison between specimens of identical geometry at various times in the specimen loading history.

At the left of the drawing in Fig. 1, we show the optical observations of the crack front at certain load levels during the loading. On the right, we have implied the values of the load at certain crack front positions by correlating the appearance of the fracture surface with the loading history. The values of $K_C$ calculated from these observed and implied data fall within the same range. The spread in these values could well represent the inhomogeneity in the strength of this material.

A second parameter that we can get out of these observations is a measure of the average fracture surface area per detectable acoustic emission event. Some of these numbers are shown in Fig. 1 for different regions during the slow fracture. We determined the area of a slow fracture region which was formed between two well-defined points in the loading history and divided it by the number of events which occurred during that time. This ratio is a measure of the average fracture surface area per event which for this specimen was an area of 11-37 microns squared. Comparing this to the fiber diameters of about 8 microns, you can see that these areas for the individual fracture units are small, of the order of a few fiber diameters on the average. But then again, because of the wide range in the amplitudes of the emissions that we see, we get some feeling for the wide range in the fracture surface areas, too.
We looked at various orientations of the specimens. This happens to be an LS specimen, that is, the maximum stress axis was along the fiber direction and the crack propagation direction was in the S orientation or through the thickness of the plate normal to theplies. Other orientations were the LT, TS and TL. We used these different orientations to change the dominant fracture modes in order to identify the characteristics of the acoustic emission signals generated by the various modes. Although different types of emission signals were seen, we were not able to correlate them with specific fracture processes, because the individual variations between supposedly identical specimens overshadowed any of the changes that we were able to produce.

Loading was done on an Instron machine using a constant crosshead speed, and loading was carried to failure in most instances. In Fig. 2 are shown some examples of the loading history. The solid line in each figure is the load-time curve. In the top two figures, the dotted curve is the cumulative acoustic emission event count and the dashed curve is the cumulative acoustic emission count. The difference here is that the event curve is obtained by taking each of the acoustic emission bursts and counting it as one event. The count curve is obtained by counting each cycle in the oscillatory bursts and accumulating that number. Larger amplitude events will give more counts per burst. The ratio of the slopes of these two curves, the number of counts to the number of events during a given time interval, is plotted in the bottom figures. This gives a measure of the average amplitude of the emissions at any time during the test. Also, at the bottom is plotted the event rate. You can see that this is a widely fluctuating quantity and was found to be widely erratic between identical specimens, presumably very dependent upon the exact nature of the pre-existing flaws and the exact nature of the fracture process.

The curves shown in Fig. 2 are only examples for the unaged and the aged materials. There was no typical curve for the two conditions. Sometimes the unaged material would load up and fracture all the way through, and in this example, the biggest crack step was in the aged material, but that wasn't necessarily typical.

At the normal 60 dB gain settings of the detection amplifiers, a great many of the emission bursts would saturate the amplifiers. At various times in the loading history, for example, where the crack was growing stably, we reduced the gain to increase the dynamic range of the amplitude measurements. This is indicated by the 60 dB and 40 dB notations during some time periods in Fig. 2. During tests on other specimens, 20 dB gain was sometimes also used.

So, that's kind of an overview of what is shown in Fig. 2. It shows the erratic nature of the fracture and some of the types of data that we can get from these tests.

Now, looking at this in a little more detail, we performed some tests by loading and unloading in the elastic region. Early in the loading history, we get a few events on loading, none on unloading. Loading it back up again, no emission events occurred until the previous high load had been reached and exceeded, then more emission events would start coming out. This would continue until the specimen was loaded up to a point such as indicated by a small inflection or load drop on the loading curve. Upon unloading from that point, emission events occurred during the unloading part of the cycle. I interpret that as being interference of the fibers coming back together in the fracture region. If the load is cycled to that load level two or three times, all the emission activity goes away. The point of all this is that any characterization of the fracture behavior or the state of the specimen, based upon just the number of emission events alone, is going to be very dependent upon past loading history, and it will be very hard to interpret.

Another effect is seen on the bottom curves of Fig. 2. The average amplitude of the emission events with time during the loading history, as measured by the ratio N/Ne, goes through a maximum and then levels off at some lower value. This was typical of all specimens. We interpret the maximum as being due to the growth and stabilization of the pre-existing flaws, growing out from localized weaker regions into the stronger matrix. The constant amplitude region is then the growth from that point on, through the presumably stronger composite material. A second point is that the average value for the unaged specimens was always greater than the average value for the aged specimens.
of the average amplitudes of the emissions at varying times during the history. In Table I, these data are summarized along with the strength data for the three classes of materials tested, shown in order of increasing moisture resistance from left to right. The least resistant material, designated SC-2-2, had the graphite fibers treated during manufacture of the composite to substantially reduce the strength because of the fibers and the matrix. One result of this was that all of the bend specimens failed in compression on the bottom side of the specimen, so we can't really compare that material to the results of the others. You can see there's a big difference in the strength of that material between the unaged and the aged condition, but no consistent difference in the average amplitude of the emissions. In the other two materials, there was consistent difference in the strength properties and in the acoustic emission amplitudes, between the unaged and the aged materials.

Considerable effort went into identifying the different fracture mechanisms by frequency spectral analysis of the acoustic emissions. I don't want to spend any time describing the methods used today, since we have reported them to you before and they are well documented in the literature. We did identify several distinct spectral types. Again, correlation with particular fracture mechanisms was not possible. Also, one other observation was that the variability between the frequency spectrum of individual acoustic emission events within a given spectral type was much greater in this material than in any previous material that we have studied. That could possibly be due to the greater variation in the geometries of the emission sites in this very complex composite material, or it could be due to the dispersion in the acoustic path between the source and the detection transducer.

### Table I.

Summary of Comparative Strength and Average Crack Step Size for the Various Test Conditions

<table>
<thead>
<tr>
<th>Material (Orientation)</th>
<th>Unaged</th>
<th>Aged</th>
<th>April</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-2-2</td>
<td>126</td>
<td>76</td>
<td>70</td>
</tr>
<tr>
<td>SC-3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SC-4</td>
<td>100</td>
<td>67</td>
<td>93</td>
</tr>
<tr>
<td>SC-5</td>
<td>150</td>
<td>93</td>
<td>76</td>
</tr>
<tr>
<td>SC-6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3. Cumulative amplitude distribution - F(V)
Frequency spectral data for one specimen is shown in Fig. 4. Again, the load-time curve showing the acoustic emission record is shown. Above it, different frequency spectral types and when they were observed to occur during the loading are indicated for several time periods during the test for which the recorded signals were analyzed. Most of the acoustic emissions were white noise (WN), i.e., having a very broad frequency content, but tending to have either of two rather distinctive spectral shapes as indicated at the top of Fig. 4. At any given time the relative numbers of the other different types are indicated by the density of the lines shown. For example, most of them were white noise during the first analysis period, while quite a few of them were Type III near the end of the period. That's how this display was intended to read.

You can see some correlations between the occurrence of the different spectral types and the loading history; for example, at the first deviation from linear loading, the first occurrence of the Type III emission was noted. Also, the first occurrence of the Type I emissions was immediately preceding and during a major catastrophic crack growth step, and these occurred throughout the rest of the history of the specimen. I don't want to make any more of that than is indicated here, but for each specimen analyzed, there was some indication that the frequency spectral information can be used as an indication of where you are in the crack growth history. Also, comparing these data for the unaged specimen with those of the aged specimen, there are some differences. They are subtle and, at this point, it is not possible to sort out the exact mechanisms operating. The fact that differences can be seen is encouraging, however.

In order to apply signal characterization to the test of a large component structure, attention must be paid to the highly attenuating and dispersive nature of wave propagation in these materials. Figure 5 shows the velocity and the attenuation vs. frequency in the B-1 material. Both plate specimens and bar specimens were used to obtain these data. You can see it is very attenuating at higher frequencies and very dispersive at lower frequencies. This must be taken into account in a test on a structure. Of course, crossply laminates would have different characteristics than this, so in each case these properties of the material would have to be measured.
and the spectral information may provide the information required.

Now, where are we going? We would like more accurate data taken over a wider dynamic range, and we are building equipment now to do this. It will collect in real time several characteristics of the emission events and display these characteristics as they change during a test.

Also, Dick Elsley of our laboratory has developed computer software to sort out and cross-correlate these characteristics, making this chore less tedious and more quantitative.

Finally, Bill Pardee has developed a theoretical description of the contributions of the acoustic emission source, the wave propagation path between the source and the detector, and the detector response to the characteristics of the emission signal. In this formalism, these three components are separable and their effect on the received emission signal can be analyzed independently, as you will hear more about this afternoon. This theoretical work has helped in interpreting the experimental observations already, and further source modelling is expected to provide an important contribution in this area.

DISCUSSION

PROF. MAX WILLIAMS (University of Pittsburgh): Thank you very much, Mr. Graham. We have a couple of minutes left. Are there any questions?

DR. SAM NASH (Frankford Arsenal): You gave us some data on the number of events per unit area. What kind of an area are you measuring: projected area or actual area?

MR. GRAHAM: Projected area.

DR. NASH: That would be quite different from the real area.

MR. GRAHAM: You have to make up your own model for just what it means in terms of actual area according to the details of what's going on. And also, you have to phase into this the very wide dynamic range of the areas and the emission amplitudes. So, this is just a very gross number which provides a starting point for these considerations.

DR. STEVE CARPENTER (University of Denver): Where you start to get the emission and throughout the deflection, do you correlate that with a plastic strain rather than time? It looks like that begins where you begin to have some plastic strain.

MR. GRAHAM: Right. It starts building up about that point, although there are some emissions before then. I'm not sure how you would sort out the difference between plastic strain and actual irreversible microfracture processes that are going on around the pre-existing defects. No, I haven't tried to analyze it.

PROF. WILLIAMS: I have a general question to the speaker, perhaps to some of the audience. It has bothered me for a considerable length of time on acoustic measurements, and I'm going to focus on the unloading mechanisms, that the acoustic bursts, the acoustic emission energies that are indicated perhaps might be used in reverse. When one unloads the specimen, if you had a perfect crystal, presumably the burst energy could, through recombination of the atomic structure, absorb some of the energy and then lead to absorption of energy instead of the outburst of energy. The question is: has anyone measured or attempted to measure this kind of energy absorption under the unloading or recombination of energies even during the loading? The first question is the primary one that concerns me. Has anyone in the acoustic business attempted to measure the absorption of energy as a specimen is unloaded or loaded?

First crack at it to you, I suppose, Mr. Graham.

MR. GRAHAM: I'm not aware of it.
PROF. WILLIAMS: Anybody in general?

DR. CARPENTER: If you consider the absorption of energy in measuring the damping as you unload it, yes, we have measured the dislocation damping along with the acoustic emission both in loading and unloading.

PROF. WILLIAMS: With simultaneous measurements?

DR. CARPENTER: Simultaneous measurements.

PROF. WILLIAMS: That's very good. And the material, please.

DR. CARPENTER: We're working now in very pure iron with four levels of carbon concentration and also doing some hexagonal close-packed materials.

PROF. WILLIAMS: And that is a metal structure we note for the record. There has been some work in the rubbers - thermo-elastic materials - that I have been aware of which sparked my question.

Thank you very much, Mr. Graham.