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ACOUSTIC EMISSION FROM STRESS RUPTURE AND FATIGUE OF AN ORGANIC FIBER COMPOSITE

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ACOUSTIC EMISSION FROM STRESS RUPTURE AND FATIGUE OF AN ORGANIC FIBER COMPOSITE*

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ABSTRACT

A series of tests was carried out to determine the scatter in acoustic emission data gathered during stress rupture and fatigue testing of a simple fiber-reinforced epoxy composite. Single-end organic fiber/epoxy strands were monitored for acoustic emission during tensile tests to failure, stress rupture tests, and dynamic fatigue tests. During the stress rupture and fatigue tests, the plots of summation of acoustic emission counts vs time were found to resemble metal creep curves in that primary, secondary, and tertiary regions could be distinguished. Because of a significant amount of scatter, only a limited correlation can be made between the slope of the summation of acoustic emission in the steady state region and the specimen life during stress rupture and fatigue testing. In addition, flawed specimens were easily sorted out during the tensile tests. These results indicate that acoustic emission data gathered during composite fatigue and stress rupture testing might be useful for life prediction.

KEY WORDS: Acoustic Emission, fiber composite, fatigue, stress rupture

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INTRODUCTION

Acoustic emission (AE) refers to the small amplitude transient elastic waves that are generated by rapid releases of energy within a material [1]. In the last few years, AE records have been shown to be very useful in the microstructural interpretation of pressure testing of filament wound vessels. For example, AE has been shown to be sensitive to winding pattern changes, different fibers, different matrix materials, and both winding and artifically induced flaws [2,3].

As far as we are aware, previous studies of the AE generated during stress rupture, (i.e., time under sustained loading) and dynamic fatigue of fiber/epoxy composites are quite limited [4,5,6]. Only a few specimens were tested in each of these studies, and hence the scatter that occurs in the AE from such tests was not determined. The object of our research was to examine many specimens to determine the amount of scatter in AE data, and to continue to assess the usefulness of AE data gathered during such tests. Because AE data gives microscopic information, it may have great significance in the development of theoretical models for the phenomena of stress rupture and fatigue of fiber/epoxy composites.

PROCEDURE

Specimen Preparation

A spool of single-end organic fiber (Kevlar 49 with 285 filaments)[1] was dried in a vacuum oven at 82° C (180° F) for a minimum of 24 h. Then approximately one layer was stripped from the outside and discarded. The single-end fiber was impregnated with Union Carbide ERL 2258/ZZL 0820 (100/30) epoxy and wound by a vacuum filament winding process [7] into strand specimens. The specimens were gelled at 93° C (200° F) for 3 h and cured at 163° C (325° F) for 2 h on the steel winding frame. Using a previously successful technique, specimens with a 13-cm gage length were bonded to mechanical clamps with room-temperature-cure epoxy adhesives [7]. The tensile strength, stress-strain behavior, and stress-rupture behavior of such strands of organic fiber are well documented in Ref. 8. The average fiber volume was about 72 percent. The rational behind the use of these simple composite specimens was two-fold. First, many specimens could be tested because they were very cheap, and second, since the specimens were very simple, it was expected that the AE response would be easier to interpret than with more complicated composite specimens.

Acoustic Emission Equipment

Commercial AE equipment and transducers were used to monitor the AE during the tests. A piezoelectric AE transducer was coupled to one of the mechanical specimen grips using a viscous resin and tape. As is shown in Fig. 1, a second dummy transducer was coupled to the opposite side of the grip so that the grip with transducers remained with its center of gravity in the line of the strand. The AE signal was processed through a preamplifier, a filter (set to pass 100 to 300 KHz), and a power amplifier. In total, the system provided some 80 to 90 dB of electronic gain as needed. The acoustic signal was presented visually in two ways. First, the signal was displayed on an oscilloscope as a function of time. In addition, a count was made of the number of times that the amplitude of the acoustic signal exceeded a voltage bias (nominally set at 1 V). The cumulative total of counts was recorded on an X-Y plotter as a function of load, time, or number of fatigue cycles.[2] In addition, during the fatigue tests a voltage control gate was used which disabled the counter during a certain portion of the load cycle.

Test Conditions

All specimens were tested at room temperature (about 22° C (72° F)) in a modified commerical testing machine. The strand clamp system was suspended between self-aligning universal joints, one of which was connected to a load cell. First, a series of strands were tested to failure using a constant cross-head rate of 0.5 cm/min. Next, a series of strands were cycled between approximately 88 percent and 12 percent of their average failure load at 10 Hz in a sinusoidal mode until each failed. Finally, a series of strands were brought to a dead weight load of approximately 88 percent of their average failure load. This dead weight loading was accomplished by lowering at a constant rate the crosshead on which the dead weight was supported. It took less than 10 s to load the strands in this manner. The strands then remained under load until failure occurred.

During each test, the AE was monitored. The relatively high load levels for the fatigue and stress rupture tests were chosen so that the testing time for each specimen would be relatively short: on the order of 4 h or less.

EXPERIMENTAL WORK

Tensile Tests

Fig. 2 shows the results of typical tensile tests with organic fiber strands. This figure shows the band within which the sum of AE vs the load fell for 14 specimens, the actual curves for two of these specimens, and the actual curves for two flawed specimens. Fig. 2 also shows a typical strain vs load curve during a strand tensile test. The average tensile strength based on the 16 specimens tested here was 3,710 MPa (538 Ksi). Fig. 3 shows the sum of AE vs load for a typical tensile strand test as well as the same data for two specimens which were unknowingly flawed during attachment of the AE transducers. All tensile tests were carried out at an electronic gain of 80 dB.

Fatigue Tests

Two difficulties were encountered during the fatigue tests. First, a large share of the specimens failed at the clamps in spite of a number of modifications in the adhesive joint design. Second, at the same point in each load cycle, extraneous AE was often generated in the adhesive bond of the joint. Visual observation indicated that this AE often came from rubbing of particles of the adhesive that had broken loose from the adhesive but still remained bonded to the strand. This latter difficulty was largely overcome by using the voltage control gate to ignore all the AE generated at loads below 75 percent of the average tensile failure load. In tests where there was no adhesive generated AE, it was verified that the slope of the summation of AE vs number of test cycles did not significantly change when the voltage control gate was set to 50 percent of the average tensile failure load. Attempts to eliminate adhesive AE generation by using different adhesives were not successful.

The results of 10 fatigue tests are shown in Fig. 4. This figure shows the summation of AE as a function of the number of test cycles. All of these specimens failed properly in the gage length.

Stress Rupture Tests

The results of 19 stress rupture tests are shown in Fig. 5. Here the summation of AE is shown as a function of time. All of these tests were at 80 dB electronic gain.

DISCUSSION

The discussion and interpretation of the results are based on the premise that the large majority of the AE generated during these tests is associated with fiber filament failure. The basis for this assumption has been more fully discussed previously [2 and 3]. Briefly, the filament failure stresses are on the order of 50 times the resin failure or the interfacial debonding stresses. Thus, the energy released by the latter two mechanisms in the form of stress waves is expected to be much lower than that released by filament failure. The result is that AE electronic gains, which allow the experimenter to conveniently process the stress waves generated by filament failures, are too small to provide the amplification necessary to process the majority of stress waves generated by the two matrix-related damage mechanisms.

The strand tensile tests with AE were performed first to provide a background to help in the interpretation of the stress rupture and fatigue AE data. These tests indicate that strand specimens which fail (because of handling induced flaws) at loads below the lowest strength associated with the typical distribution of strength of the organic fiber are easily distinguished at low loads by the AE data. For example, the AE data in Fig. 3 for specimen 17 indicated by the substantial early AE at about 40 percent of the average strand tensile strength that this specimen was flawed. As is shown, the specimen failed at about 78 percent of the average strand strength. This result shows that AE testing has promise as a nondestructive test technique for fiber composites.

As Fig. 2 shows, even for these very simple composite specimens, one cannot use summation of AE to pick out the strong and the weak specimens within the typical distribution of strand strengths. We suggest that successful sorting of strengths by summation of AE would only work if failure in the strand took place as a result of filaments progressively breaking at only one location along the length of the fiber. The most likely situation is that this type of mechanism is occurring at several locations in each strand and that the number of locations is not a constant from strand to strand. This situation results in the total AE counts-to-failure during a tensile test changing radically from strand to strand as shown by the scatter in Fig. 2.

The AE data gathered during the stress rupture and fatigue tests have a number of similarities. In both cases, the summation of AE as a function of time or the number of cycles resembles metallic creep curves in that primary, secondary (or steady state), and tertiary regions can be distinguished. During the first few minutes of testing, filament breakage occurs at a decreasing rate until averaged over a period of time an approximately steady rate of breakage occurs. Just prior to failure, the rate of breakage progressively increases giving an AE warning of impending failure. Figs. 4 and 5 show that there is some correlation between the life of the specimen and the slope of the steady state summation of AE. The specimens with less slope tend to last longer. The exceptions to this tendency are probably related to the differences in the number of locations along the length of each strand where filaments are progressively breaking. This phenomena again leads to scatter.

The fact that the steady state region exists indicates that AE may be a useful tool for the study of the effect of different environments on the stress rupture or fatigue life of these organic fiber composites. For example, during the steady state region, the environment could be changed while noting whether or not the slope of the AE curve changed. An increase in slope would indicate a more detrimental environment. Using this technique would allow a relatively rapid screening of many different environments because the experimenter would not have to wait for specimens to fail to see if their stress rupture behavior had been degraded or improved.

Typically, the AE data gave a warning of impending failure during the dynamic fatigue tests at approximately 85 to 98 percent of the fatigue life. The AE data also gave a warning of impending failure during the stress rupture tests. Fig. 5 illustrates that the warning was usually on the order of 1 to 4 min. The fact that AE gives clear indication of impending failure implies that AE could be used as a tool to enable the experimenter to stop a test just prior to failure so that other inspection techniques could be used to study the test generated flaws.

It is of interest to point out that the total number of AE counts at failure was on the average significantly higher for the tensile tests than for the stress rupture tests. For example, most of the stress rupture specimens had approximately 10,000 or less counts (at 80 dB) just prior to failure, while most of the tensile specimens had approximately 20,000 to 80,000 counts (at 80 dB) at failure. This implies that the filament breakage was not as extensive in the stress rupture specimens as in the tensile specimens. This phenomena is to be expected in stress rupture because of the stress level dependence of the stress rupture mechanism in the organic fiber [8]. Thus, with increased time at load during the stress rupture tests, progressive damage occurs at fewer locations along the length of the specimen.

A comparison of the stress rupture data of Fig. 5 with the AE obtained during a stress rupture test of an S-glass/epoxy pressure bottle is shown in Fig. 6 (taken from Ref. 4). This comparison shows that data in both cases are similar. This implies that one could expect more complicated filament wound organic fiber/epoxy pressure vessels to result in AE data very similar to Fig. 5.

CONCLUSIONS

- For tensile, fatigue, and stress rupture tests, the AE data showed a good deal of scatter for macroscopically identical specimens and tests.
- During stress rupture and fatigue tests of the organic fiber/epoxy strands, the summation of AE vs time curves were found to resemble metal creep curves. These curves gave an AE warning of impending failure.
- As a result of scatter, only a limited correlation can be made between the slope of the steady state region of the AE curve and specimen life.
- The existence of the steady state region implies that AE may prove useful in studies of the effect of different environments on the stress rupture and fatigue life of organic fiber composites.
- Based on the results of these tests, AE data should be obtained from many fatigue tests of more complicated organic fiber composite specimens in order to determine if scatter precludes life prediction.

ACKNOWLEDGMENT

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FOOTNOTES

1. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

2. When excited by an incident stress wave, the AE transducer rings at a characteristic frequency. Thus, a single acoustic emission event normally gives several counts.

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Figure Captions

Fig. 1. Test setup with Acoustic emission transducers

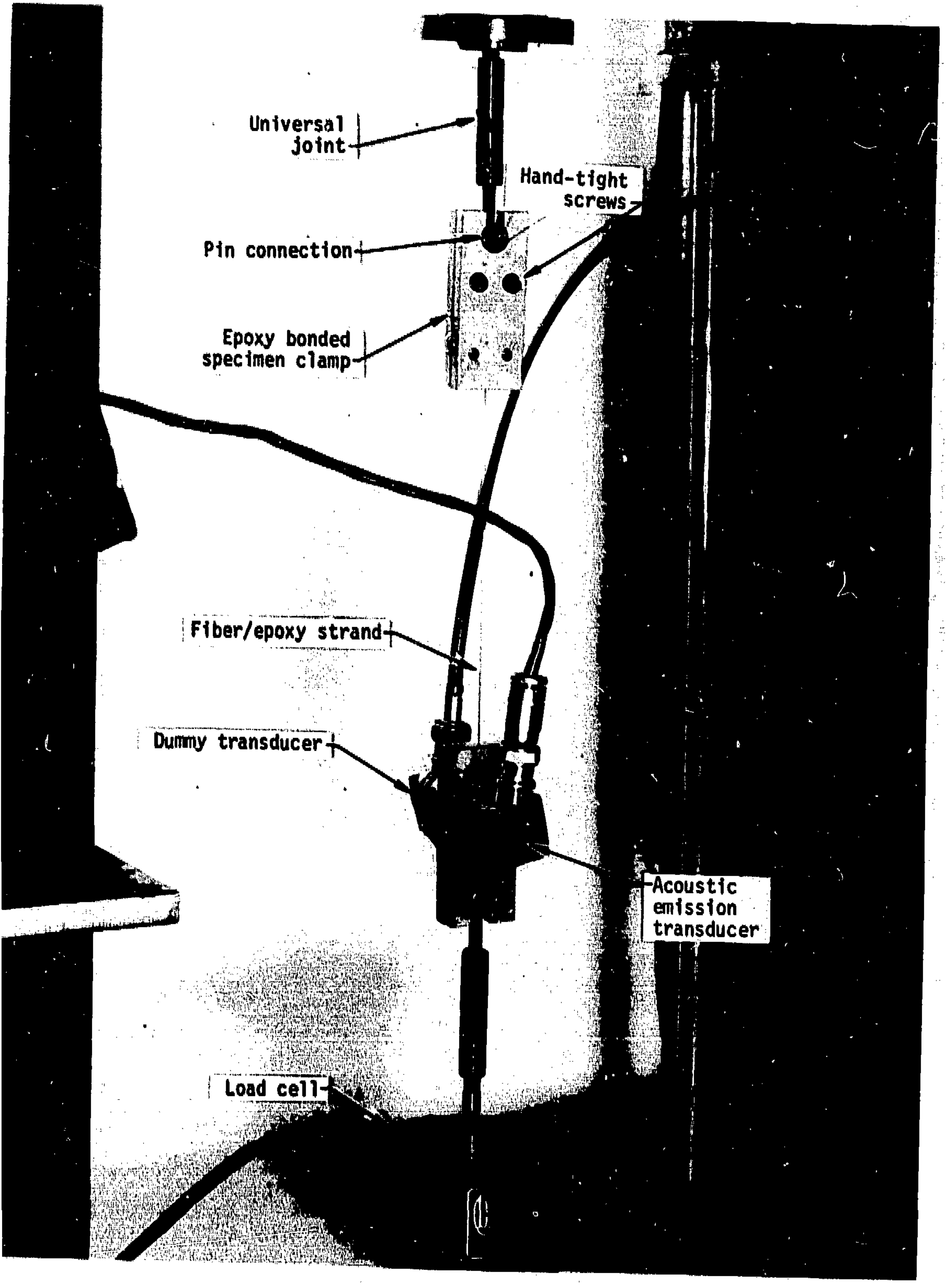
Fig. 2. Summation of acoustic emission for organic fiber/epoxy strand tensile tests, and typical strain vs load for strand tensile test.

Fig. 3. Acoustic emission of flawed and unflawed organic fiber/epoxy strand specimens.

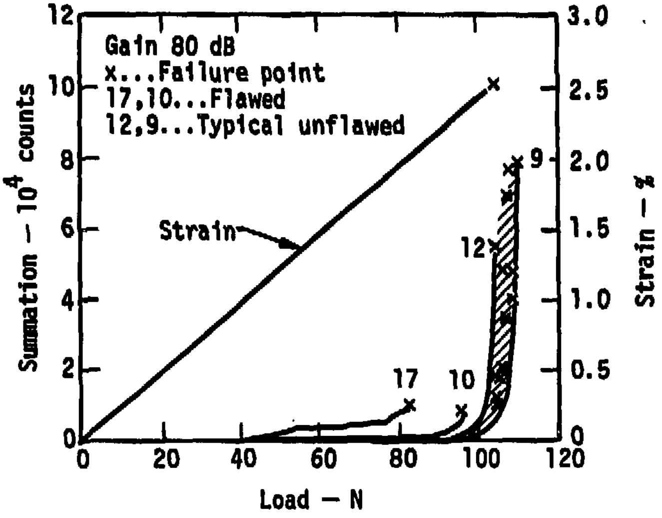
Fig. 4. Summation of acoustic emission above 75 percent of tensile failure load during fatigue tests vs number of cycles. Specimen numbers shown.

Fig. 5. Acoustic emission counts during stress rupture of organic fiber/epoxy strands.

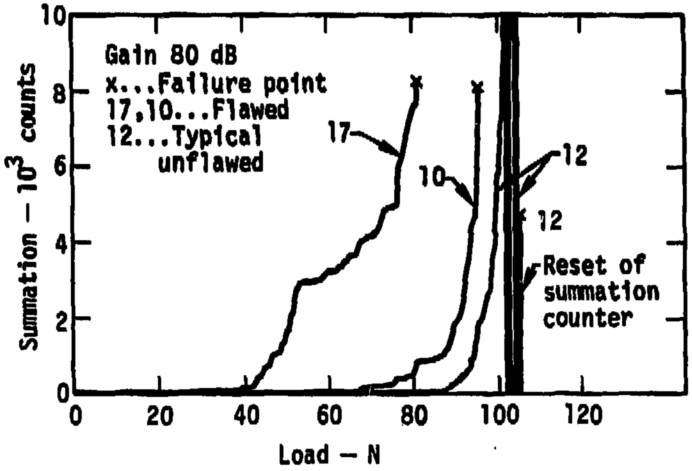
Fig. 6. S-glass/epoxy pressure vessel stress rupture summation of acoustic emission vs time at 83 percent of expected failure pressure (85 dB) (taken from Ref. 4).



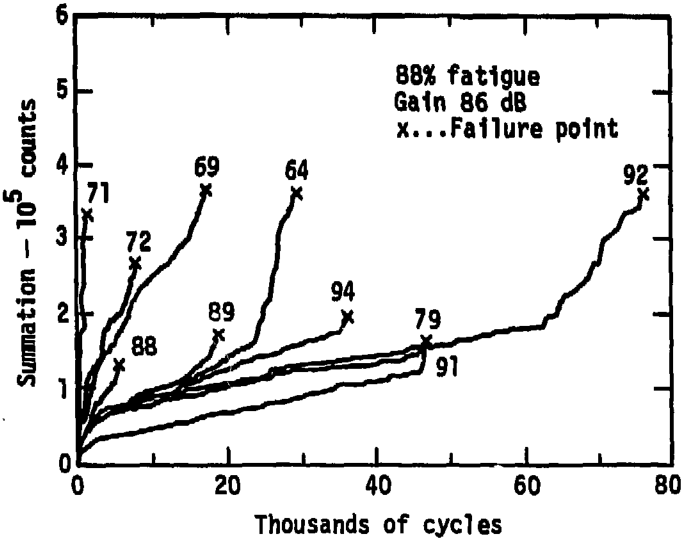
Hamstad - Fig. 1



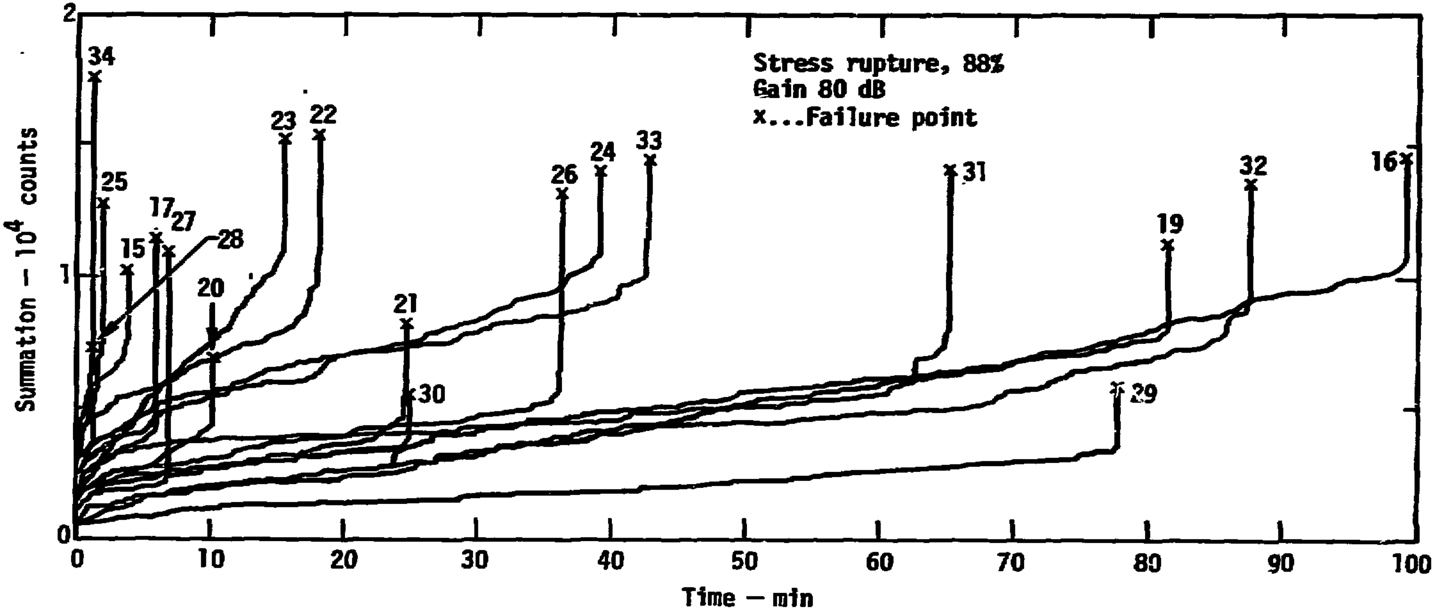
Hamstad - Fig. 2



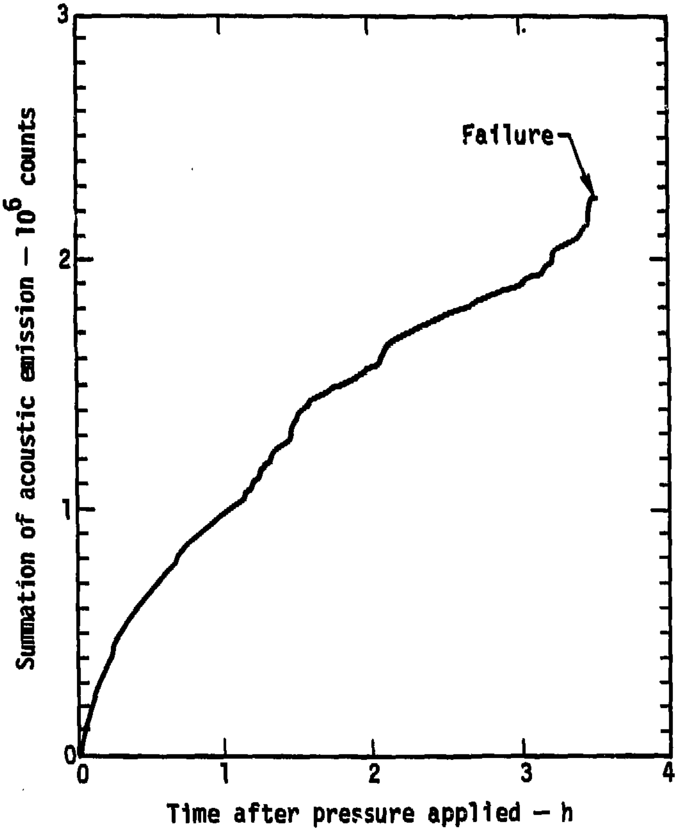
Hamstad - Fig. 3



Hamstad - Fig. 4



Hamstad - Fig. 5



Hamstad - Fig. 6