Acoustic Emission Characteristics of Pultruded Fiber Reinforced Plastics under Uniaxial Tensile Stress

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Abstract

This paper presents a new method that filters out the acoustic emission (AE) hits associated with non-fiber breakage mechanisms in Fiber Reinforced Plastics (FRP). The proposed method is carried out by removing low-amplitude AE hits until the cumulative plot of the remaining AE hits vs. the applied load coincides with the cumulative AE signal strength vs. load plot. The lowest remaining amplitude is taken as the borderline amplitude between fiber breakage and non-fiber breakage hits. A series of pure unidirectional fiber specimens was subjected to tensile tests and extensive scanning electron microscope (SEM) studies in order to validate the technique. The tensile tests of pultruded FRP specimens, consisting of more complex fiber structures, were also conducted. By applying the developed technique to the AE data from these tests, it was found that the borderline amplitudes fall in the same range for the specimens composing of the same material. This proved the low-amplitude filtering technique was a reliable tool to separate the AE data associated with fiber breakage from the data corresponding with non-fiber breakage mechanisms. Other aspects of the AE characteristics obtained from testing the pultruded FRP specimens are also discussed.

Introduction

Acoustic emission (AE) has been proven as one of the appropriate nondestructive techniques for quality control and periodic in-service inspection of the fiber reinforced plastic (FRP) structural components. This is because AE is reliable, cost effective, and capable to detect various defect sources in FRP. This has led to the establishment of several standard procedures for assessing the significance of defects by AE. However, to date these procedures have not effectively determined defect types using AE data. Even though there have been attempts to conduct signature analysis and failure mechanism characterization, these techniques are still preliminary and require further exploration on their applications.

This research study focuses on the AE characteristics of fiber breakage in FRP specimens. Specifically, an amplitude filtering concept is developed and subjected to a validation with FRP coupons having unidirectional fiber arrangement. After the validation is completed, the amplitude filtering is applied to pultruded FRP specimens. This type of specimen provides a more complex fiber structure representing a normal practice usage. The borderline amplitude, which separates between fiber break and non-fiber break signals, is estimated for each specimen. The findings of this study show that the amplitude filtering technique is very reliable in identifying fiber breakage mechanism in FRP specimens using AE data. In addition, other unique characteristics of the fiber breakage mechanism such as duration and number of breaks are found in this study.

Theoretical Background

Fiber breakage or fiber fracture is defined as the mechanism at which an FRP component is under tensile stress and the fiber strain reaches the ultimate value. Other mechanisms that can occur in FRP include matrix cracking, fiber-matrix debonding, delamination between layer, and fiber pull-out.(1)

Naturally, different failure mechanisms occur in FRP composites. Thus, it is not practical to design a test specimen that exhibits only fiber breakage. This leads to a concept of studying a coupon with only unidirectional fibers under a tensile loading. This type of specimen is the simplest form for a fiber breakage investigation.

Results from many studies have shown that fiber breakage of FRP is associated with high-amplitude AE hits whereas other mechanisms (e.g., matrix cracking, etc.) are related to lower-amplitude hits.(2-8) Additionally, high signal strength is believed to be another characteristic of AE from fiber breakage. This is attributed to the fact that Young's modulus and the tensile strength of the fibers are significantly higher than those of matrix, while the typical ultimate strains of the fibers and the matrix are approximately the same. Therefore, much of the strain energy released during the test of FRP comes from fiber breakage. Since the strain energy release is directly proportional to AE signal strength, the majority of the signal strength is the result of fiber breakage.(9) Also, it is shown that fiber breakage can occur in the early stage of a tensile loading and the number of breaks increases exponentially with the increasing load.(10)

Based on the above AE characteristics of FRP, it can be concluded that the cumulative AE signal strength with respect to the increasing level of applied loads should correspond with the cumulative number of fiber breaks. Moreover, the cumulative AE signal hits with respect to the increasing loads should correspond with the cumulative number of all failure mechanisms including, but not limited to fiber breaks. The schematic representation of this concept is shown in Fig. 1a. Further, if low-amplitude signals which are associated with non-fiber breaks are filtered out from the entire AE data, the cumulative plot of the remaining hits with respect to the loads should line up with the cumulative signal strength plot as presented in Fig. 1b. Note that all axes of Figures 1a and 1b are normalized to eliminate the difference in units. From Fig 1b, the lowest amplitude remaining after filtering is observed as the borderline between the fiber break and non-fiber break hits.

Experimental Program I: Unidirectional-Fiber Specimens

The study in this part is to determine the efficacy of the amplitude filtering technique. Therefore, it is necessary to conduct tension tests of coupon specimens having fibers only in the direction parallel to the tensile stress for this purpose. Moreover, to investigate the relationship between fiber breakage and its AE characteristics, extensive scanning electron microscope (SEM) studies are conducted to examine the failure progression of the FRP specimens.

Five FRP coupons made of Derakane 411-100 vinyl ester resin and reinforced with purely unidirectional glass fibers in the longitudinal orientation were prepared. The dimensions of the coupons were 6-in. long, 1.5 in. wide, and 0.1 in. thick with a reduced section at the middle (dogbone shape). The reduced section had a constant width of ¼ in. AE was monitored during the test through a Physical Acoustics Mistras AE data acquisition system with a R15 sensor (resonates at 150 kHz). Each coupon was taken up to different maximum load levels including 45%, 60%, 85%, 87.5%, and 100% of the ultimate load. The SEM analysis was conducted after the specified load level was reached to observe the microscopic failure mechanisms on the surface of the specimen.

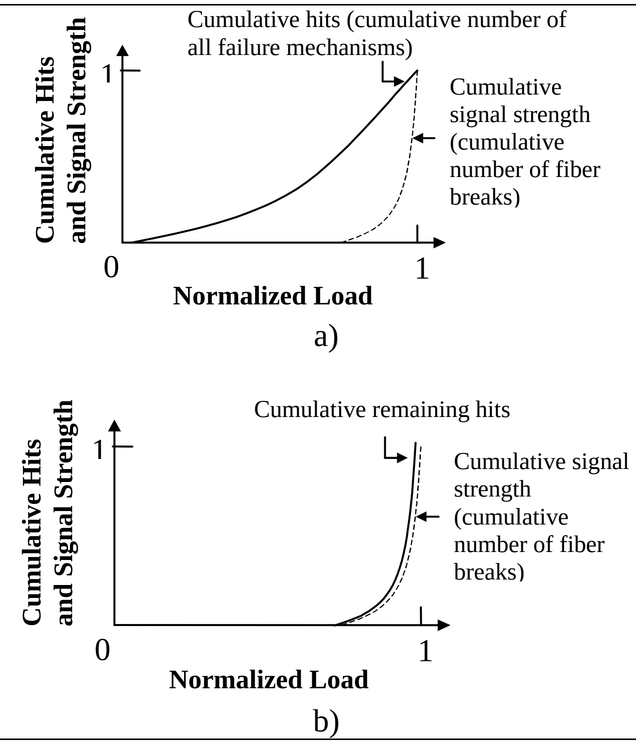
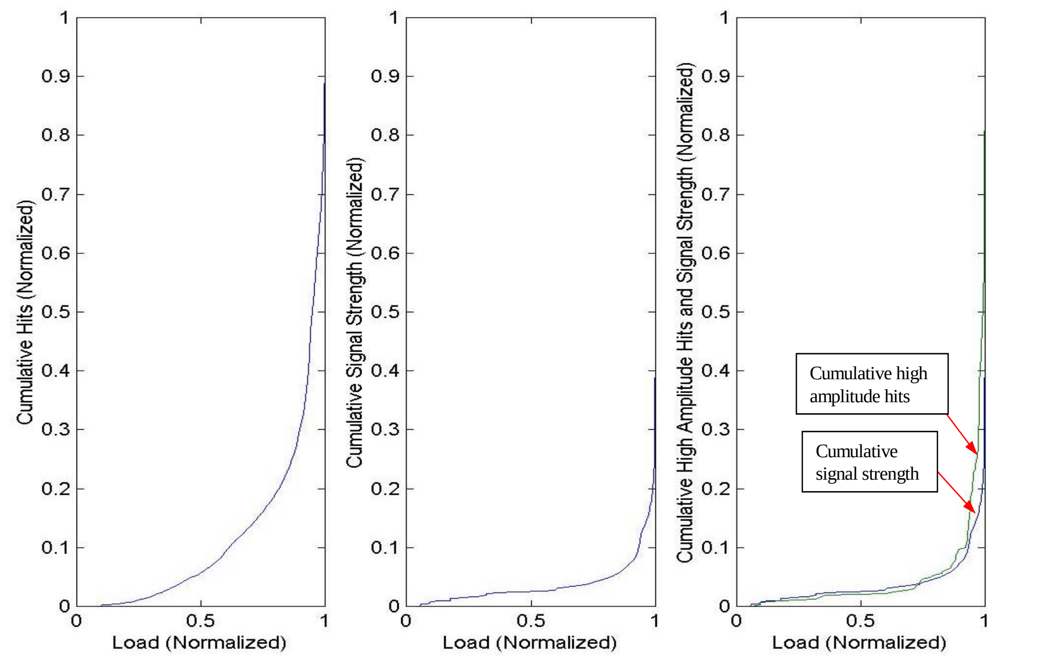


Fig. 1. Idealized schematic plots of normalized cumulative hits and signal strength vs. load: a) before and b) after low-amplitude hits are filtered

The results from the SEM showed that matrix cracking mechanism occurred first in the tested coupon. Then fiber breaks were observed. After that, fiber-matrix debonding took place at the tip of the fiber breaks. At the ultimate load, delamination and fiber pull-out were found.

Additionally, the results from the SEM observation of each coupon examined with its associated AE data showed that the number of actual fiber breaks from the SEM photographs was in good agreement with the number of high-amplitude hits and cumulative signal strength. Therefore, the high amplitude and high signal strength characteristics of fiber breakage are validated and the low-amplitude filtering can be applied to estimate the borderline amplitude of the AE data. Figure 2a shows the normalized plot of cumulative AE hits vs. load of the specimen that was taken to ultimate. As indicated previously, this plot is an approximation of the cumulative damage in the specimen. Figure 2b shows the normalized plot of cumulative signal strength vs. load for the same specimen. Based on the SEM observations, this plot is an approximation of the cumulative number of fiber breaks. As shown from these plots, there is a clear difference between the shapes of both curves.

Next, the low-amplitude hits, which are associated with non-fiber breakage mechanisms, are removed from the entire AE data. As doing this, the shape of the plot of the cumulative remaining hits vs. load becomes similar to that of cumulative signal strength vs. load plot. At the point when the hits having amplitude lower than 74 dB are removed, these two plots are almost identical (see Fig. 2c). Therefore, it is concluded that the borderline amplitude is defined as 74 dB. This can explain that the AE hits having amplitude equal or above 74 dB are associated with fiber breakage while those having amplitude below such level involve non-fiber breakage mechanisms for this type of FRP specimen.



a) b) c)

Fig. 2. Normalized plot of cumulative hits vs. load before and after filtering for the specimen taken to failure: (a) cumulative hits vs. load (b) cumulative signal strength vs. load (c) cumulative high amplitude hits (≥ 74 dB) and signal strength vs. load.

Experimental Program II: Pultruded Specimens

The objective of this study is to apply the low-amplitude filtering technique to FRP composites having a more complex fiber arrangement, in this case pultruded FRP. This study is also to determine the reliability of the amplitude filtering technique.

Pultruded FRPs consists of unidirectional fiber layers but also are alternated with chopped strand mat layers to gain strengths in the transverse direction. Five coupons with reduced sections were cut from original full-scale pultruded beams. Three different fiber-resin combinations were selected as described below:

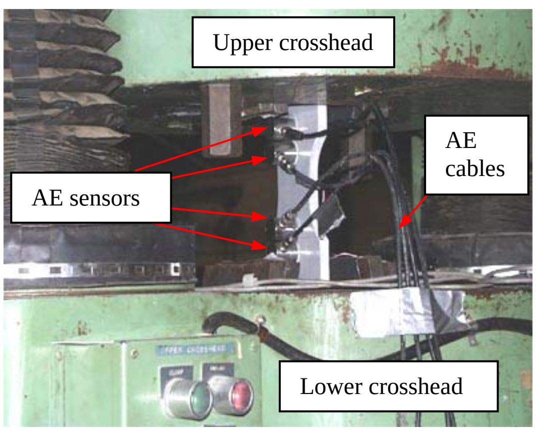
1. Specimen L1: glass fiber-isopthalic polyester resin
2. Specimen L2: glass fiber-isopthalic polyester resin
3. Specimen L3: glass fiber-vinyl ester resin

4.Specimen L4: glass fiber-vinyl ester resin
5.Specimen L5: glass/carbon hybrid fiber-vinyl ester resin

Each coupon had different dimensions ranging from 20 to 30 in. long, 5.25 to 6 in. wide, and 0.5 to 0.6 in. thick. The width of the reduced sections also varied from 3 to 3.25 in. Loading was applied to the longitudinal axis of the coupons, which increased monotonically to failure. Figure 3a shows the test setup of specimen L2.

Two full-scale FRP beams were also subjected to 4-point bending tests to failure for a practical representation. Specimen F1 was made of glass-isopthalic polyester, while specimen F2 consisted of glass-vinyl ester material combination. Both specimens had a cross section of a wide-flange shape, which was WF 12 in.x 12 in.x 0.5 in. The entire beams had a length of 98 in. Bottom flanges at mid length were machined into a reduced section (3 in. wide) to ensure tensile failure. Also, there was a 4-in diameter circular hole at the midspan of specimen F1, and a 6-in. diameter hole for specimen F2. The test setup of specimen F2 is presented in Fig. 3b

Four acoustic emission sensors resonating at 150 kHz, were used with a Mistras data acquisition system. The sensors were arranged in two pairs. Each pair of sensors was located at each end of the reduced section of the specimens (see also Fig. 3a).



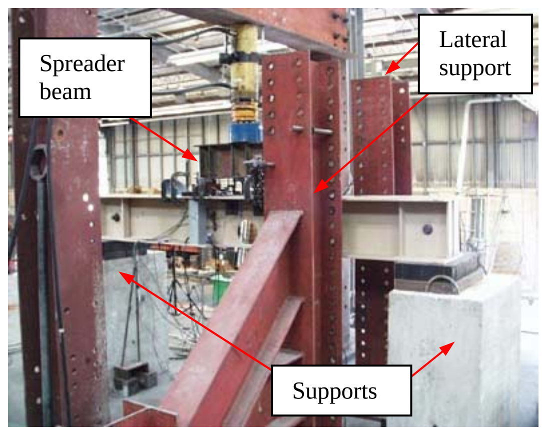


Figure 3. Test setup: a) coupon specimen L2 b) full-scale specimen F2

Results and Discussion

The low-amplitude filtering was applied to estimate the borderline amplitude between fiber breakage and non-fiber breakage hits. The borderline amplitude from each sensor on a specimen was determined and the results of average borderline amplitudes from all sensors are shown in Table 1. The specimens that were made of the same materials were found to yield the same borderline amplitude ranges. Specimen L5 which was made of hybrid fiber-vinyl ester resin exhibited relatively lower borderline amplitude when compared with those made of glass fibers. This agrees with the results from Valentine's study, which can be attributed to the small diameter of carbon fibers.[(11)] Up to this point, it can be concluded that the low-amplitude filtering technique is a reliable tool for identifying AE hits from the fiber breakage mechanism in FRP structures.

Three representative amplitude vs. load plots from each type of material constitution are shown in Fig. 4. High-amplitude hits in glass-vinyl ester specimens occur earlier than those of glass-isopthalic polyester specimens. This is due to the effect of flexible vinyl ester resin, which permits a higher strain in the specimen leading to more breaking of the brittle fibers. High amplitude hits in the hybrid specimen (L5) begin even earlier than those of glass-isopthalic polyester specimens. The carbon fibers are very brittle and susceptible to having imperfections introduced during the fabrication process. This causes premature fiber breaks during the test. It is also noted that the total number of AE hits from the hybrid specimen is considerably greater than those of the other specimens. This is attributed to the small diameter of carbon fibers, which yield more number of fibers per unit cross-section area. Therefore, there are more fibers to break when compared with glass specimens.

High-amplitude AE hits from all specimens when approaching to the ultimate load (starting from approximately 90% of ultimate) are found to be associated with a very long duration. This duration can be up to 1 second. Figure 5 is the progression of amplitude vs. duration relationship of specimen L1 at different load levels. The figure shows that the long-duration hits are observed only after 90% of the ultimate load. It is believed that this long duration characteristic is a continuation of fiber breakage and fiber pullout. This is because the SEM study observed that fiber breaks occurred in conjunction with fiber pullout in the last stage of the test. The long duration is not likely to be from a continuation of fiber breakage and the other mechanisms such as matrix cracking or debonding since the fiber breaks in conjunction with these mechanisms were found to occur at the earlier stage of the test.

The other possible cause of this event is that the long duration hits are a continuation of more than one fiber break. This is due to the high number of fiber breaks during failure. The fiber breaks occur almost simultaneously, such that the AE data acquisition system cannot separate the signal from each break.

Table 1. Summary of low-amplitude filtering results

Specimen	Material	Average borderline amplitude (dB)
L1	Glass/isopthalic polyester	76
L2	Glass/isopthalic polyester	76
F1	Glass/isopthalic polyester	76
L3	Glass/vinyl ester	80
L4	Glass/vinyl ester	81
F2	Glass/vinyl ester	81
L5	Hybrid/vinyl ester	68

Conclusions

1. The low-amplitude filtering technique is developed to separate fiber breakage of FRP from other failure mechanisms. The technique is done by removing low-amplitude AE hits (associated with non-fiber breakage) from the entire AE data until the plot of cumulative remaining hits vs. load coincides with the cumulative signal strength vs. load plot. The lowest remaining amplitude is taken as the estimated boundary between fiber breakage and non-fiber breakage hits.

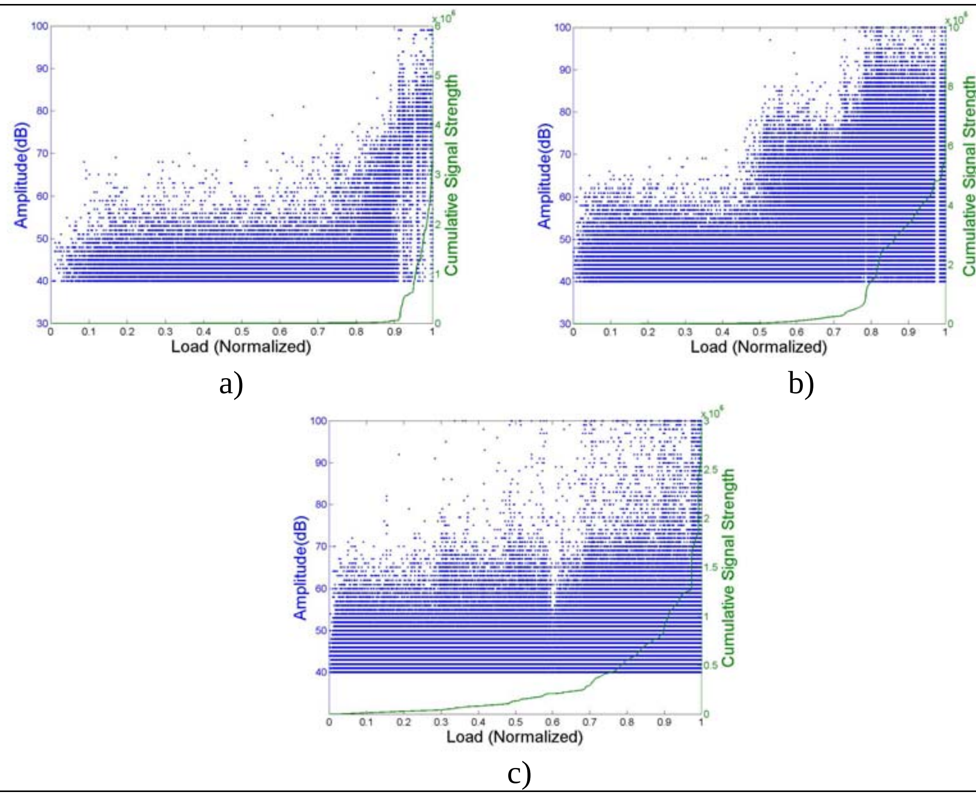


Figure 4. Amplitude superimposed with cumulative signal strength vs. load (normalized): a) specimen L1 b) specimen L4 and c) specimen L5

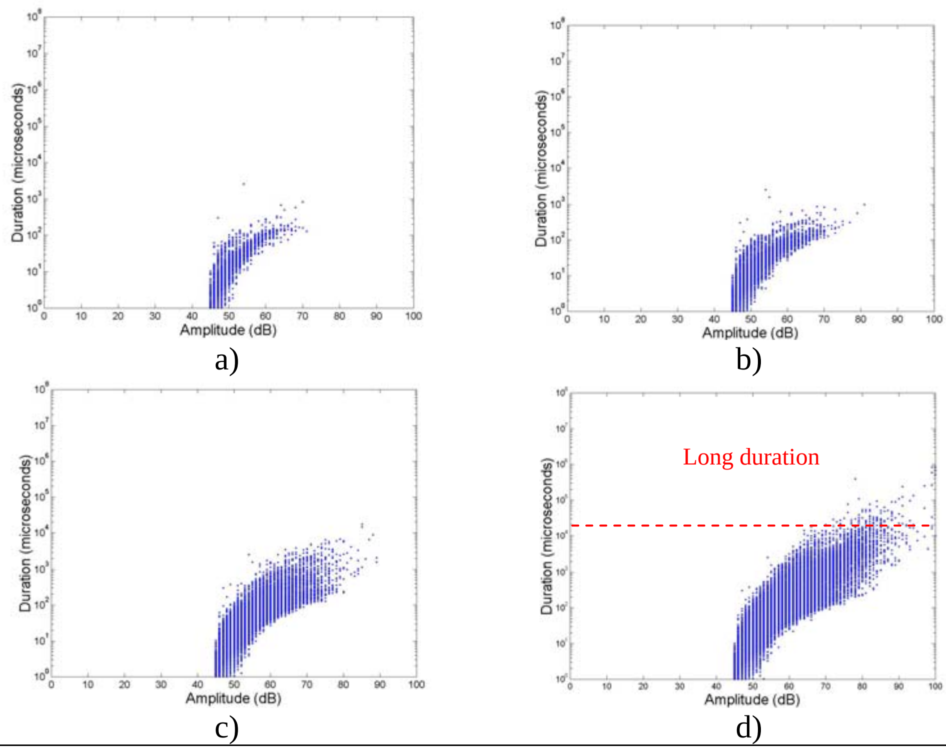


Figure 5. Progression of amplitude vs. duration plot for specimen L1:
a) at 50% b) at 80% c) at 90% and d) at 95% of ultimate

2. The concept of low-amplitude filtering technique is proven in this study to be justified. The technique is also proven to be very reliable even for FRP specimens with complex fiber structure.
3. High-amplitude hits in glass-vinyl ester specimens occur earlier than those of glass-iso specimens. This is because flexible vinyl ester resin allows a higher strain in the specimen leading to more breaking of the brittle fibers.
4. High-amplitude hits in the hybrid specimen (L5) begin earlier than those of glass-vinyl ester and glass-iso specimens. Carbon fibers in hybrid FRP usually are very brittle and are easily damaged during the fabrication process. Therefore, carbon fibers are likely to have premature breaking.
5. High amplitude/long duration signals detected at the latest stage of the test provide unique characteristics for this type of testing. It is believed that these signals are from fiber breaks continuing to fiber pull-out or multiple fiber breaks occurring simultaneously.

References

1. T.J. Fowler and E. Gray, "Development of an Acoustic Emission Test for FRP Equipment," Preprint 3593, Annual Convention, ASCE, Boston, MA, April 1979.
2. T.N. Crump, "Acceptance Criteria for Acoustic Emission Testing of FRP Tanks," SPI/CARP Meeting Paper, Atlanta, Georgia, June 1981.
3. J.M. Berthelot and J. Billaud, "Analysis of the Fracture Mechanisms in Discontinuous Fibre Composites Using Acoustic Emission," 1st International Symposium on Acoustic Emission from Reinforced Composites, 1983, pp.1-10.
4. L. Li and J.H. Zhao, "The Monitoring Damage Growth Processes in Glass Fiber Reinforced Composite by Amplitude Analyses," 2nd International Symposium on Acoustic Emission from Reinforced Composites, Montreal, 1986, pp.90-95.
5. M.C. Merienne and J.P. Favre, "Identification of the Acoustic Signals Generated by the Rupture of SIC Fibre/Metallic Matrix Composites," 3rd International Symposium on AE from Composite Materials AECM-3, Paris, 1989, pp.304-312.
6. T.N. Crump and M.A. Droge, "The Characterization of Fiberglass Reinforced Plastics Using Acoustic Emission," *Managing Corrosion with Plastics*, Vol. 4, pp. 91-95, National Association of Corrosion Engineers, Texas, 1979.
7. A.A. Pollock, "Acoustic Emission Amplitude Distributions," *International Advances in Nondestructive Testing*, 7:215–239 (1981).
8. J.L. Walker and E.v.K. Hill, "Amplitude Distribution Modeling and Ultimate Strength Prediction of ASTM D-3039 Graphite/Epoxy Tensile Specimens," 4th International Symposium on AE from Composite Materials AECM-4, Seattle, 1992, pp.115-131.
9. *Nondestructive Testing Handbook-Second Edition, Volume 5, Acoustic Emission Testing*, R.K. Miller (Tech. Ed.), P. Mcintire (Ed.), American Society for Nondestructive Testing (ASNT), 1987, Metals Park, Ohio.
10. C. Zweben, "Tensile Failure of Fiber Composites," AIAA 6th Aerospace Sciences Meeting, New York, January 1968, pp.2325-2331.
11. D. Valentin, Ph. Bonniau, and A.R. Bunsell, "Failure Mechanism Discrimination in Carbon Fibre-Reinforced Epoxy Composites," *Composites*, 14(4):345–351 (1983).