Statistical Methods Applied To Acousto-Ultrasonic Technique

by

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(ABSTRACT)

The growth in the extent of applications of composite materials, particularly in commercial products, has been dramatic and carries an implied mandate for effective methods for material quality evaluation. The cost of composite materials dictates that non-destructive test methods be used. At the same time, the nature of composites limits the use of conventional techniques such as radiography , eddy-current or ultrasonics. Recently, a new technique known as the Acousto-Ultrasonic (AU) technique, has been developed and appears to hold promise as a method for the evaluation of composite material quality.

Implementation of the AU method is examined using the zeroth moment method developed by Henneke et. al.. A new parameter termed as Acousto Ultrasonic Factor (AUF) has been defined for this purpose. The behavior of the AUF response to specimens of known quality is investigated statistically. It is found that the transformed/actual readings follow a Beta distribution and that specimens of different quality are readily distinguishable using the statistical analysis of the AUF response. Reasonable future steps for translating these findings into efficient quality evaluation methods have been suggested.

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1.0 Introduction

Composites are materials of the future. The wide usage of these materials for space, military and commercial applications at present reflect the truth of the statement. The main advantages of using composites lie in their high strength and stiffness to weight ratios. In addition to these advantages, composite materials can be tailored according to design specifications. Though the strength and stiffness of composites as observed in the laboratory are very attractive compared to metals, there is a wide scatter in these properties when used for production components. This offsets some of the advantages composites offer over monolithic materials.

Quality control of composites [1] is quite unlike that encountered in monolithic materials. Though the basic philosophy still remains the same, the approach taken may be different. This can be attributed to the following reasons:

- The heterogeneous and anisotropic characteristics of the individual materials have marked influence on the final product.

- The various combinations of the fiber and matrix and the parameters which control the fabrication process, all have an influence on the end product.

Such being the case, most of the conventional test methods applicable for monolithic materials cannot be immediately adapted to composites. This has prompted a search for new testing methodologies which give better insight into the nature and behavior of composite materials.

Nondestructive evaluation techniques are being widely used for characterization of metallic materials and also serve as methods of quality control. Some of these popular nondestructive evaluation techniques [2] are now being used for material characterization of composites. Thus the main objective of NDE is to detect the various types of defects in structural members and evaluate the influence of these defects on the life of composites. Further, considering the nature of composites, NDE acquires a greater importance and can contribute significantly to the acceptance of composites in both commercial and military applications. Some of the NDE techniques that are currently used for quality control of composite products are,

1. Visual checks
2. Radiography
3. Dye-penetrants
4. Acoustic Emission
5. Ultrasonic Techniques
6. Thermography

However, due to the limitations encountered in the above techniques, one is forced to look for new techniques or modify existing ones. A fairly new technique known as the Acousto - Ultrasonic (AU) technique or the Stress Wave Factor (SWF) technique holds good promise in this regard. This technique is a hybrid of Acoustic Emission and Ultrasonic techniques and combines the advantages the two techniques offer.

The AU technique used in this study was developed at Virginia Tech by Henneke et. al. [4]. In this technique, the material is quantified and qualified in terms of a number known as the stress wave parameter. This number can serve as a quality index of a particular material. Comparisons of the values of stress wave parameter at different points in the same specimen or with

that of different specimens yields the basis of discrimination between the two specimens. In the present work, a slight modification is made in defining this stress wave parameter. This is due to the fact that the stress wave factor does not have a universal definition. A parameter termed as the Acousto-Ultrasonic Factor (AUF) has been defined for this purpose. This is discussed in detail in the later chapters.

In this study a statistical approach to discriminate between specimens of the same material using the AU technique is explored. The values of the AUF obtained are modified using a linear relation. A statistical distribution is assumed and various parameters relating to this distribution are calculated. A Beta distribution is assumed for this purpose and the validity of this model is checked by goodness of fit tests. Further, the feasibility of using the AU technique combined with statistical methods for quality control of composites is investigated. This is done by varying the parameters of the Beta distribution, thus simulating the quality of the material itself. After having determined the trend of the cumulative distribution frequency (CDF) curves, an attempt is made to fix a lower bound for the curve. The appropriate conditions which would help in identifying the position of the CDF curve relative to the lower bound are investigated.

2.0 BACKGROUND

The term composite in a composite material signifies that two or more materials are combined on a macroscopic scale to form a useful material. The three commonly accepted types of composite materials are

1. Fibrous Composites
2. Laminated Composites
3. Particulate Composites

Composites have become highly valued engineering materials because of the unlimited variety of material properties that can be obtained from very large number of possible fiber-resin choices, lay-up orientations and configurations. Many properties can be improved in composites compared to monolithic materials. Some of them being stiffness-weight ratio, strength-to-weight ratio, corrosion resistance, wear resistance, thermal conductivity and acoustical insulation. However composites are inherently more flawed than metallic materials. The flaws in composites can be classified as

• Manufacturing flaws
• Flaws due to service

Manufacturing flaws are flaws which may be introduced during the fabrication process. Some of the important flaws of this type are

1. Improper or uneven cure of resin
2. Fiber misalignment
3. Variation of fiber-volume fraction
4. Delaminations and transverse cracks
5. Impurities
6. Voids

Flaws in composites are also introduced during service conditions. This is because any component may be subjected to static overload, fatigue, impact etc., Thus one can list flaws introduced during service.

1. Delaminations
2. Fiber cracks
3. Matrix cracks

So, one has to have ways of detecting these flaws, in components before and during their service. Nondestructive evaluation has been used for defect detection and material characterization. Some of the nondestructive techniques which are currently being used to evaluate composites are detailed here under.

2.1.1 Acoustic Emission :

Several studies have shown that the acoustic emission technique can be used successfully for evaluating flaw severity. This is possible because the acoustic emission signals have their source in the flaws or defects. However, this being a active technique it cannot be used to detect defects unless

and until the component is subjected to load. This technique can be used for monitoring structural integrity, predicting onset of damage and pinpointing the source of damage. Crack initiation, crack growth etc., all give rise to acoustic emission signals. The acoustic emission technique is very sensitive compared to other nondestructive methods especially with regard to microcrack formation. Acoustic emission can be used as a method of Quality Control [5] as the acceptance/rejection criteria can be established in terms of some acoustic emission parameter. Further, the acoustic emission technique finds an application in proof testing.

2.1.2 Ultrasonic Testing :

This is the most widely used technique for nondestructive evaluation and characterization of composites. There are some basic parameters which can be measured easily by performing ultrasonic testing and which can be used for evaluating and characterizing the material. They are

1.   Velocity of ultrasonic waves

2.   Attenuation of waves

3.   Frequency content of the waves

The above parameters can be measured as a wide range of ultrasonic instrumentation and transducers are currently available.

The velocity of ultrasonic wave in composites depends on their elastic constants and densities. So, if one can measure the ultrasonic wave velocities, the elastic constants of the composite could be determined. Kriz et. al. [6] have shown that by measuring longitudinal and shear wave velocities in different directions of the composite, the elastic constants can be calculated. Similarly the porosity of a composite can be determined by measurement of two or more ultrasonic wave velocities. Velocity measurement is also frequently used for thickness measurement purposes.

Conventional ultrasonic testing, ie., pulse echo and through transmission can also be used effectively for detecting damage in composites. While one can use pulse echo techniques for location of flaw and size of the flaw, the through transmission technique is useful in estimating size and location of the inplane flaws.

If accessibility to the transducers on both sides of component is limited, than one can use the pitch-catch technique. As all these methods use amplitude of reflection from flaws to quantify the flaws, it requires a skilled operator to identify these signals.

Ultrasonic attenuation can be used for detection of voids and moisture content. It is a known fact that voids can affect the strength and durability of composites. As voids in composites scatters the ultrasonic waves, an increase in voids increases attenuation. However attenuation is different for different ultrasonic frequencies. This principle is made use of by ultrasonic c-scan. In this technique, the defects are mapped on the outline of the actual component. Thus the signals from the interior of the component are presented in plan form. However, no depth information about the flaw can be obtained unless one looks simultaneously at the A-scan. Thus, delaminations and voids, can be easily detected. Further this technique is capable of detecting material damage due to fatigue and impact damage.

Thus, to summarize, ultrasonic techniques interact with the material in a mechanical manner and thus are related to the mechanical state of the material.

2.1.3 Acousto-Ultrasonic Technique :

This is a relatively new technique which has found application in the area of damage detection and material response. As the name suggests, it is a hybrid of acoustic emission and ultrasonic techniques. It incorporates the advantages of both techniques. This technique was originally proposed by Vary et. al. [3]. At present the acousto-ultrasonic technique has acquired a broader perspective. There have been several different definitions of SWF used in the literature. Vary et. al. [3] define SWF in terms of threshold crossings of the voltage-time while Henneke et. al. [4] have

used moment approach to define SWF. However both methods have shown a good promise in extracting information about the material.

Vary et. al. [7] have show correlation of fiber composite tensile strength with ultrasonic stress wave factor. They have shown that higher values of SWF correspond to greater inter-laminar shear strength.

Duke et. al. [8] have shown good correlation between SWF values and failure location and that this technique correlates well with Moire interferometry. Stiffler et. al. [9] have shown that decrease in SWF calculated by moments method correlates well with reduction of stiffness of graphite-epoxy specimen subjected to fatigue tests. Kiernan [10] has shown that this method can be used to evaluate graphite/epoxy laminates and aluminum/graphite. Thus, one can conclude that the acousto-ultrasonic method holds much promise as regards to characterization of materials.

In the present study, the approach taken by Henneke et. al. [4] has been adopted. However, a slight modification in the definition of the stress wave parameter is made. A new parameter known as Acousto-Ultrasonic Factor (AUF) is defined. This is discussed in detail in the next chapter.

By definition, Quality Control is the series of regulatory process through which one measures actual quality performance, compares it with standards and acts on the difference. This basic philosophy towards the quality control of composite products is no different from that of monolithic metals, though the approach may be slightly different because of the special characteristics of the composite material as discussed earlier. Thus one can enforce the quality control activities [1] for composite products in three different stages.

1.   Quality control of constituents

2.   Control of fabrication process

3.   Inspection of final product

In our study, we have concentrated on the quality control of final products of composites. Nondestructive techniques have been used for quality control of composites and have been discussed earlier. In this study, an acousto-ultrasonic approach has been adopted and statistical

analysis is performed on the stress wave parameter. An accept/reject criterion is then suggested based on these statistical tests.

3.0   METHODOLOGY

3.1.1   TECHNIQUE

Nondestructive testing (NDT) is being used as a powerful technique for defect detection and evaluation of composite materials. Of the various methods, a new method known as the acousto-ultrasonic technique holds significant promise in this regard. A very important benefit of this technique is the measurement of a stress wave parameter which one might be able to use as a quantitative indicator of the mechanical quality of the material.

The AU technique as developed by Vary et. al. [3] will here be known as the conventional method. A schematic diagram of the set up of this technique is as shown in Figure(1). In this method, stress (ultrasonic) waves are input to the material using an ultrasonic pulser with the help of a piezoelectric transducer known as the sending (transmitting) transducer. A receiving transducer placed on the same side of the specimen picks up these stress waves which are measured by conventional acoustic emission instrumentation. The SWF is defined as the product of the number of times the voltage level of a single signal exceeds a set threshold level,the pulse repetition rate and

the length of predetermined measurement time interval [11].The schematic diagram describing this is shown in Figure (2). The SWF measure is given by:

$$E = NGR \qquad [1]$$

where

    N = Number of threshold crossings contained in each burst. (Quantity)

    G = Predetermined time interval. (Time)

    R = Pulse repetition rate. (Quantity / Time)

Note that E is nondimensional.

    The value of the SWF is not unique for each material and structural configuration but is dependant on transducer characteristics,mounting pressure, type of coupling agent used between transducer and specimen, distance between transducers the propagation characteristics of the material and the condition of the component. Thus this method is instrumentation dependent and repeatability of a specific number may be affected.

    An alternate technique was developed by Henneke et. al. [4]. This differs from the conventional method in the way SWF is defined. The alternative method is very similar to the conventional method, in that ultrasonic waves are passed through the material with the help of a sending transducer and the resulting stress waves are picked up by a receiving transducer. The two transducers are mounted on the same side of the specimen and the distance between them held constant. The various parameters like mounting pressure on the transducers, coupling agent etc. are kept constant. The schematic of the experimental setup is as shown in Fig(3).

Spectral analysis is then performed on the received signal. Talreja [12] has noted three classes of parameters which are necessary to evaluate the material. They are the location,shape and scale parameters which represent the frequency spectrum and can be defined by considering the spectrum to be a plane figure that is closed on the frequency axis. The shape parameter is of particular interest and can be evaluated from the frequency spectrum, by taking various moments of the frequency spectrum about the amplitude axis. Thus one can take the formula for differential area,multiply it
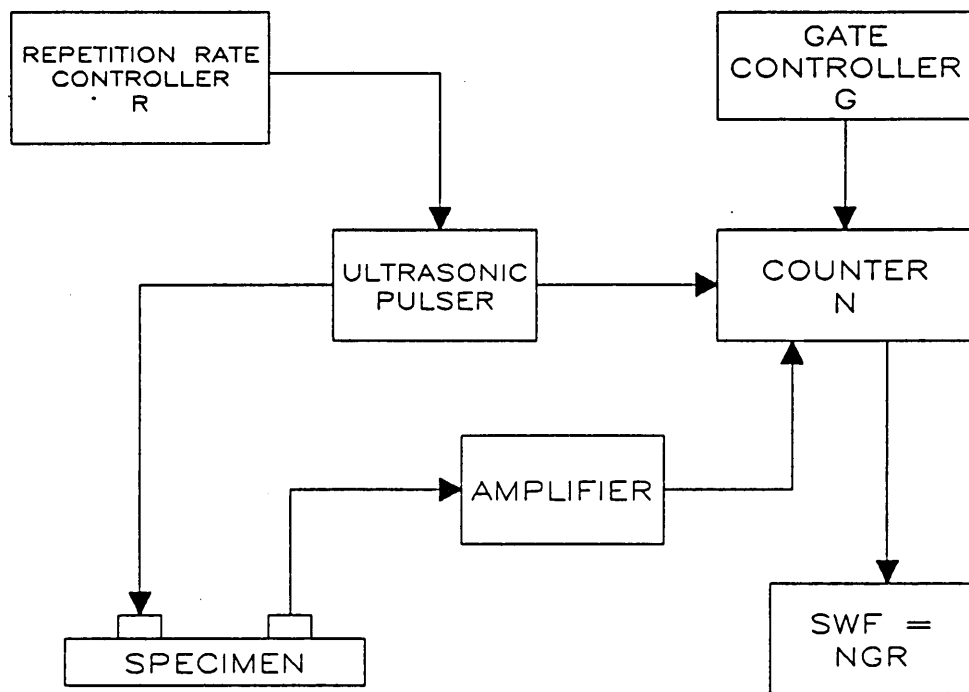
Figure 1.   Schematic diagram showing the set up of the conventional technique.
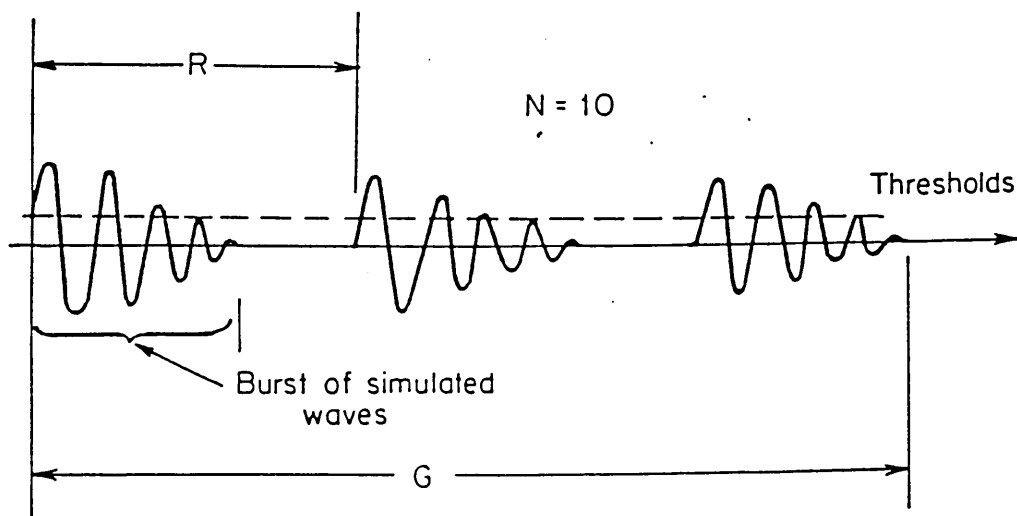
Figure 2. Diagram describing the parameters of the conventional method.
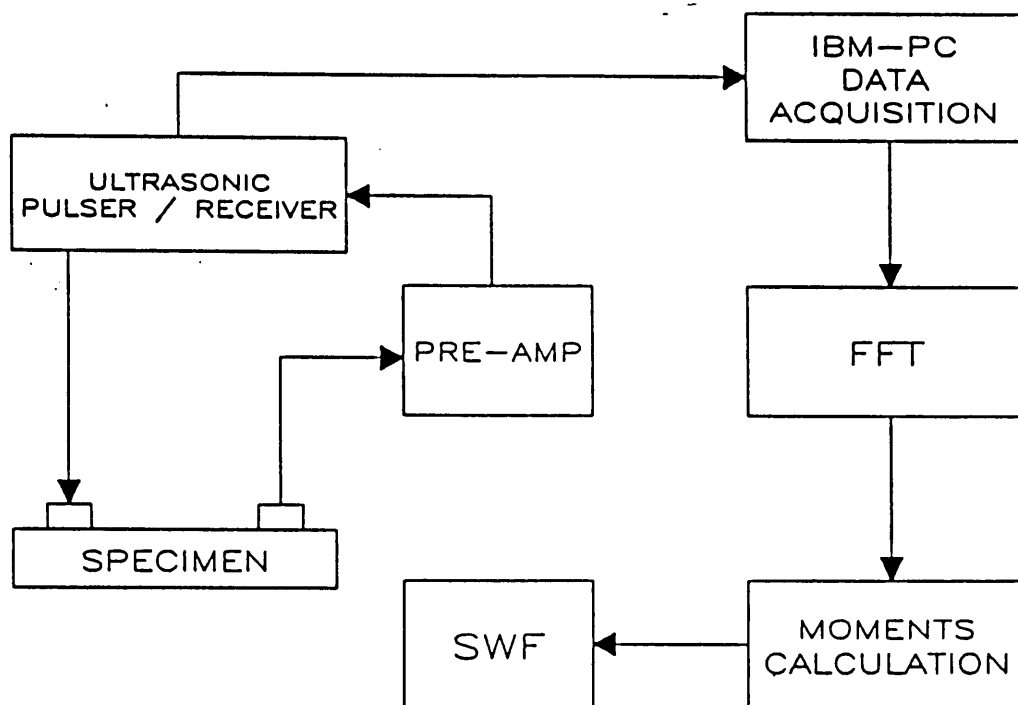
Figure 3. Schematic diagram showing the set up of the moments method.

by frequency raised to the nth power, and integrate under the frequency spectrum curve. Thus the nth moment can be defined by

$$M_n = \int_a^b s(f)(f^n)df \qquad [2]$$

where

n = 0,1,2,.....

a = f_l is the lower frequency of interest.

b = f_u is the upper frequency of interest.

where s(f) is power spectral density, f the frequency. By taking n = 0, one can get the zeroth moment which has been used as an alternate measure of SWF. The SWF as used herein is defined as the square root of the zeroth moment. That is SWF is given by

$$SWF^2 = M_o \qquad [3]$$

where

$$M_o = \int_0^b s(f)df \qquad [4]$$

where

b = f_u is the upper frequency of interest.

and is the area under the frequency spectrum (zeroth moment). This is shown in Fig(4).

A major advantage of this technique is the elimination of the threshold level and several other instrumentation parameters. This improves the repeatability of SWF values to a very large extent and thus this technique is used in this study.

As discussed earlier, there are some conflicting opinions about how to definine the stress wave factor precisely. Talreja [13] defines the SWF as zeroth moment whereas Henneke et. al. [4] define it as the square root of the zeroth moment. A new parameter termed as Acousto-Ultrasonic Factor(AUF) is defined here and this AUF has been used in the present study. AUF is similar to stress wave factors defined by Henneke et.al. [4]. Here the area under the frequency spectrum is
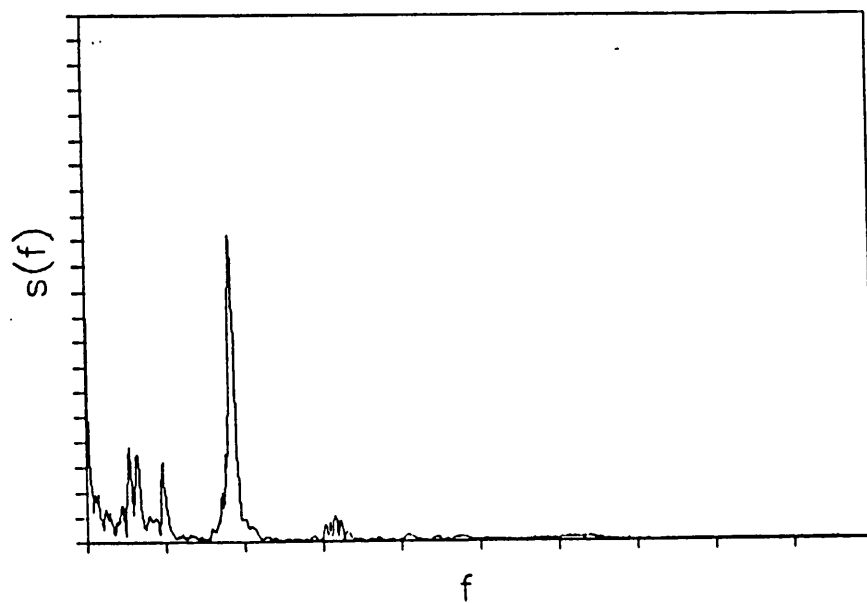
Figure 4.   Diagram describing the parameters of the moments method.

divided by the difference of the frequeny limits under which the area is evaluated. Then the square root of the resulting quantity is defined as AUF. Thus AUF can be represented by the following equation

$$AUF^2 = \frac{1}{(f_2 - f_1)} \int_{f_1}^{f_2} s(f) df \qquad [5]$$

Comparing equation [5] and equation [3] we see that the area under the frequeny spectrum is divided by the gated frequency. This is done because the divisor will be a constant and does not affect the final value of the AUF. It should be noted that we are considering the AUF as just another parameter with which one can evaluate the material responses.

3.1.2   STATISTICAL APPROACH

Material anomalies or defects generally occur in composite materials at random. They are caused by variation of feed stock materials, the production control parameters and the chemical behavior of the composite constituents. Composite structure performance depends upon the volume and distribution of defects in the material. It is suggested here that statistical methods may be used to infer material quality from the AUF measure of defect distribution in a composite material.

There are many statistical methods that may be used to characterize the behavior of sample data and to support inference about the process from which the data is obtained. Of the many methods [14], two that are meaningful for the present application are :

1.   Method of moments.
2.   Method of maximum likelihood.

It is hypothesized that AUF readings conform to a Beta distribution [14]. Data are taken using known materials and the mean and the variance calculated for the observed data. The above

methods are then used to determine parameters of a beta distribution. The reasons for assuming the beta distribution are as follows :

1. A beta distribution is applicable for continuous variables.

2. It is a two parameter distribution, hence yielding great flexibility in data fitting.

3. The AUF variables lie between the values zero and one.

4. For a large subset of conceivable parameter values, the beta distribution is moderately asymmetric and skewed.

The method of moments and method of maximum likelihood [14] are used to estimate the parameters of the beta distribution. Then the Kolmogorov - Smirnov goodness of fit test [14] is used to evaluate the fit of the beta distribution to the SWF data.

3.1.2.1   Beta Distribution

A random variable x is said to be distributed as the Beta distribution if the density function is given by

$$f(x) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{(\alpha - 1)} (1 - x)^{(\beta - 1)} \qquad [6]$$

$0 < x < 1$

where α and β are parameters with $\alpha > -1$, $\beta > -1$. The mean and the variance are related to α and β as follows

$$Mean = \mu = \frac{\alpha}{\alpha + \beta} \qquad [7]$$

$$variance = \sigma^2 = \frac{(\alpha\beta)}{(\alpha + \beta)^2(\alpha + \beta + 1)} \qquad [8]$$

There are two methods for the estimation of α and β as described in the earlier section. They are described briefly here.

3.1.2.2   Method Of Moments

The mean and the variance are the most commonly used descriptors of the random variable. These are related to the parameters of the distribution. Thus on the basis of the relationships between moments of a distribution, it follows that parameters of the distribution may be determined by first estimating the mean and variance of the random variable. In the Beta distribution, the parameters α and β are computed by inverting equations (7) and (8). Thus,

$$\alpha = \frac{\mu^2(1 - \mu)}{\sigma^2} - \mu \qquad [9]$$

$$\beta = \frac{\alpha(1 - \mu)}{\mu} \qquad [10]$$

3.1.2.3   Method Of Maximum Likelihood

This method provides a procedure for deriving the point estimator of the parameter directly. Consider a random variable X with density function $f(x,\theta)$, in which θ is the parameter. The question is, among the possible values of θ what is the value that will

maximize the likelihood of obtaining the set of observations ? Such is the rationale underlying the maximum likelihood method of point estimation.

The likelihood of obtaining a particular sample value x_i can be assumed to be proportional to the value of probability density function estimated at x_i . Then assuming random sampling , the likelihood of obtaining n independent observations x_1.......x_n is

$$L(x_i, ...,x_n; \theta) = f(x_1; \theta)f(x_2; \theta)...f(x_n; \theta)$$

which is the likelihood function. The maximum likelihood estimator is then the value of θ that maximizes the likelihood function. Due to the multiplicative nature of the likelihood function, it is often more convenient to maximize the logarithm of the likelihood function.

In our case, which has two parameters the above rationale can be extended to find the likelihood function. The final forms of the equations from which the parameters α and β are calculated are shown below.

$$\Psi(\alpha + \beta) - \Psi(\alpha) = \frac{-1}{n} \sum_{i=1}^{n} \ln(x_i) \qquad [11]$$

$$\Psi(\alpha + \beta) - \Psi(\beta) = \frac{-1}{n} \sum_{i=1}^{n} \ln(1 - x_i) \qquad [12]$$

where $\Psi(\alpha)$, $\Psi(\beta)$ and $\Psi(\alpha + \beta)$ are Psi functions of the parameters of the Beta distribution to be evaluated.

$$\Psi(z) = \frac{1}{\Gamma} \frac{d}{dz} \Gamma(z) \qquad [13]$$

is an integral equation that has been analyzed. The following equation is helpful in determining the value of $\Psi(z)$.

$$\Psi(z) = \Psi(1 - z) + \frac{1}{(z - 1)} \qquad [14]$$

and using this result, the Psi functions can be evaluated.

The maximum likelihood estimator is better than that of the method of moments in calculating the parameters of a distribution, particularly for large sample size n, since it has minimum variance (asymmetrically). Further, the former derives the estimator directly and the latter evaluates a parameter by first estimating the moments (mean and variance). Both methods have been used in our case.

3.1.2.4   Goodness Of Fit Test

A prior knowledge or belief plays an important role in application of statistical reasoning to experimental observations. Sometimes we may be unsure whether or not a particular probability distribution, or a particular form of probability distribution, which we believe to be appropriate for our observations, really is appropriate. There are certain procedures by which we may test this belief and these procedures tell us how well our data fit the probability distribution in question by comparing the observed and the expected frequencies of occurrence of a series of consecutive sets of possible values. Two such tests commonly used are Kolmogorov-Smirnov (K-S) and Chi-Squared goodness of fit tests. A K-S test is performed in our case and is described briefly.

3.1.2.5   Kolmogorov Smirnov Test

This is one of the most widely used goodness of fit tests. In this method, the experimental cumulative frequency and the assumed theoretical distribution are

compared. If there is a discrepancy larger than normally expected for a given sample size, the theoretical model is rejected. A brief outline of the K-S test follows,

For a sample size n, the set of observed data is arranged in an ascending order. From this ordered sampled data, a step wise cumulative frequency function is developed as follows.

$$S_n(x) = \begin{cases} 0 & x < x_1 \\ \dfrac{k}{n} & x_k \leq x \leq x_{(k+1)} \\ 1 & x \geq x_n \end{cases} \qquad [15]$$

where $x_1, x_2, \ldots x_n$ are the values of the ordered sample data and n is the sample size. If F(x) is the proposed theoretical distribution function, then the maximum difference between $S_n(x)$ and F(x) over the entire range of X is the measure of the discrepancy between the observed data and the theoretical model. If the maximum discrepancy is denoted by D_n then

$$D_n = \max \left| F(x) - S_n(x) \right| \qquad [16]$$

For a specified significance level s, the K-S test compares D_n with the critical value D_n^s, which is defined by

$$P(D_n \leq D_n^s) = (1 - \overset{.}{s}) \qquad [17]$$

The critical values for D_n^s at various significance levels and for various values of n can be obtained from the statistical tables [15]. If $D_n < D_n^s$, then the proposed distribution is acceptable at the specified significance level.

3.1.2.6 *Hypotheses Tests :*

These are tests which are carried out to check the validity of a parameter i.e., one needs to decide whether a statement concerning the parameter is true or false. Thus, this would involve a decision making process. Hypotheses tests [16] can be single sided or two sided. In our case a single sided test has been adopted. In this test, we check if any random parameter x is greater than or equal to a reference standard. We base our decision of accepting or rejecting on this inequality. Suppose we have a AUF of 0.75 as standard. We compare any randomly measured AUF and check whether it is greater than or equal to 0.75. If it is greater than or equal to 0.75 then hypotheses is accepted else rejected. While performing these tests, there are two possibilities which one has to look at

- If a random variable is greater than a reference standard the component is rejected
- If a random variable is less than a reference standard the component is accepted

The first possibility is termed as type I error and the second possibility is termed as type II error. In our study, we have to concentrate more on type II error, due to the nature of composites. Thus one can underline the following steps for hypothesis testing.

1. Formulate a simple hypothesis or an appropriate alternative hypothesis, which we accept when null hypothesis must be rejected
2. Specify probabilities of type I and type II errors
3. Based on sampling distribution of an appropriate statistic, we construct a criterion for testing null hypothesis against alternative hypothesis
4. Calculate from the data the value of the statistic on which the decision is to be based

5. Decide whether to accept or reject the null hypothesis, whether to accept it or whether to reserve judgement.

The most common statistic usually used concerning the mean is the one sample t-test. This t-test statistic is given by the equation

$$t = \frac{X_0 - \mu}{s}\sqrt{n} \qquad [18]$$

where

X_0 is random mean

μ is reference standard (hypothesized mean)

s is the standard deviation

n is the sample size.

This t-test static has been used in our study. Thus one can fix a critical value of t-test statistic and test the hypothesis against this.

4.0   Experimental Details

This section describes the experimental procedure adopted in the study.   The entire process can be divided into three parts. They are,

- Capturing the waveform.

- Spectral analysis of the captured waveform.

- Statistical tests.

4.1.1   Capturing the waveform

The schematic diagram of the experimental setup is as shown in figure(5).   Two transducers, one acting as a transmitter and the other as a receiver are mounted on the same side of the specimen, the distance between them being one inch center to center and kept constant with the help of plexiglass fixtures. Couplant (Ultragel) is used to ensure good contact between the specimen and the transducers and to reduce impedance mismatch. A stress wave is input to the material using a ultrasonic pulsing/receiving unit

via a sending transducer. The stress wave after passing through the material is detected by the receiving transducer. This signal is then passed through a preamplifier to the receiving unit. This signal is then digitized and stored for spectral analysis. A brief description of the instrumentation used follows:

4.1.1.1   Ultrasonic Pulser/Receiver

Accutron's model 1010PR [17] was used as a source of excitation for the input transducer. This is a broadband instrument and the pulsing/receiving parameters can be controlled over a wide range of adjustments. This has a switchable 20-40-60 dB gain. It has attenuation capabilities with both coarse (in 10 dB steps) and fine (in 1 dB steps) adjustments.

4.1.1.2   Ultrasonic Preamplifier

Accutron's model 3000 ultrasonic preamplifier [18] was used to amplify the received signals. The preamplifier has a switchable 40-60 dB gain and has a capability of amplifying signals between 5KHz to greater than 10MHz.

4.1.1.3   Sending and Receiving Transducers

Transducers manufactured by Panametrics Inc. were used for the experiments. The transducer series V109 which is broadband and has a center frequency of 5MHz was used. The sending and receiving transducers each had a diameter of one half inch.
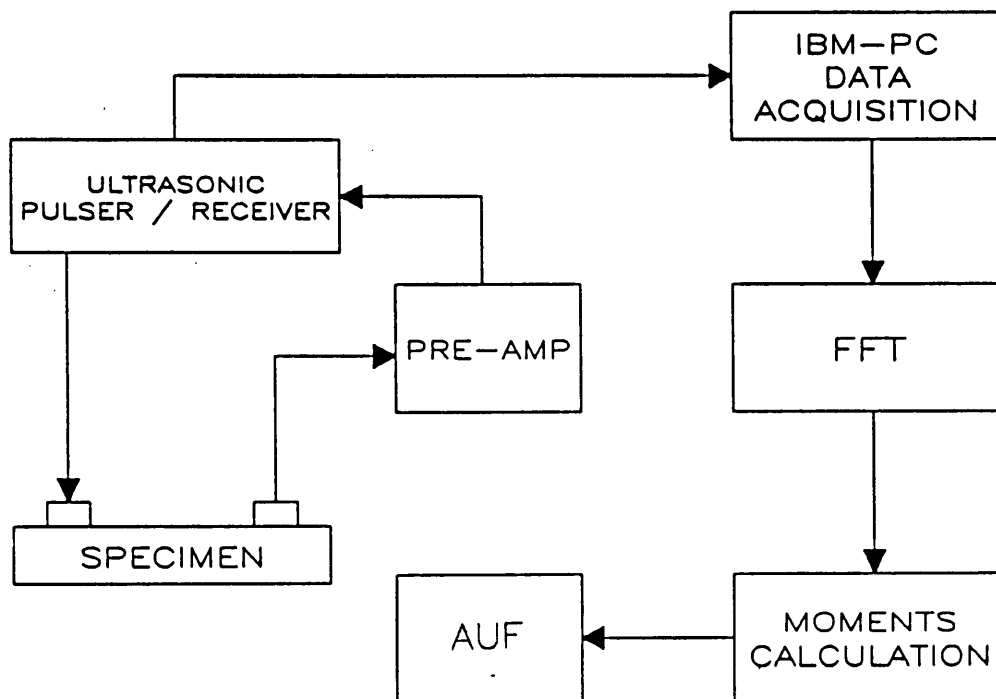
Figure 5. Schematic diagram of the experimental setup to determine AUF.

4.1.1.4   Data Acquisition System

This module is an analog to digital board which is housed in an IBM PC and appropriate software to control it. The A-D board together with the software constitutes the Personal Computer Data Acquisition System (PCDAS) which is marketed by General Research Corporation [19]. The PCDAS is a high speed data acquisition system designed specially for the IBM PC family of computers. It has an A-D board (PCTR-160) which is an 8 bit analog to digital converter with sampling rates from 150Khz to 20 Mhz in transient mode. Sampling rates of 40, 80 and 160 Mhz can be obtained in the time equivalent sampling mode. Further, it has 4K of high speed buffer memory and is capable of storing up to 4096 points of analog input at a base rate of 20Mhz. The software has capabilities of updating the waveform data (10-15 times) every second. Time delay and sweep length are controlled from the keyboard. PCDAS is capable of saving both setup parameters and the waveform data which can be used at later stages. Apart from these, the other important features include expansion of the time delay, average waveforms, define collection window (gate), perform fast fourier transforms on the gated waveform, read and write waveform data from and to the disk. Thus, one can capture waveform data, store it and display the signal by converting the screen to a virtual oscilloscope. The procedure stated above was followed for three sets of specimens, .

1.   Two carbon-carbon specimens.

2.   A graphite-epoxy specimen (GREP-1) with $[0_6]$ orientation figure(6).

3.   A graphite-epoxy specimen (GREP-2) with $[0,90_3]_s$ orientation figure(7).
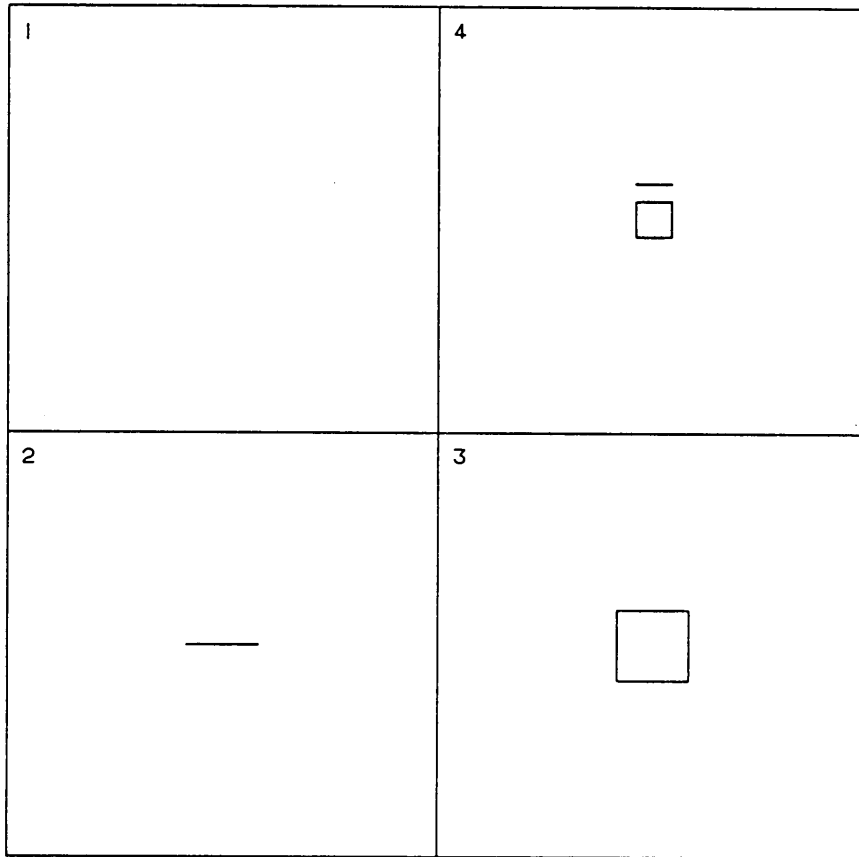
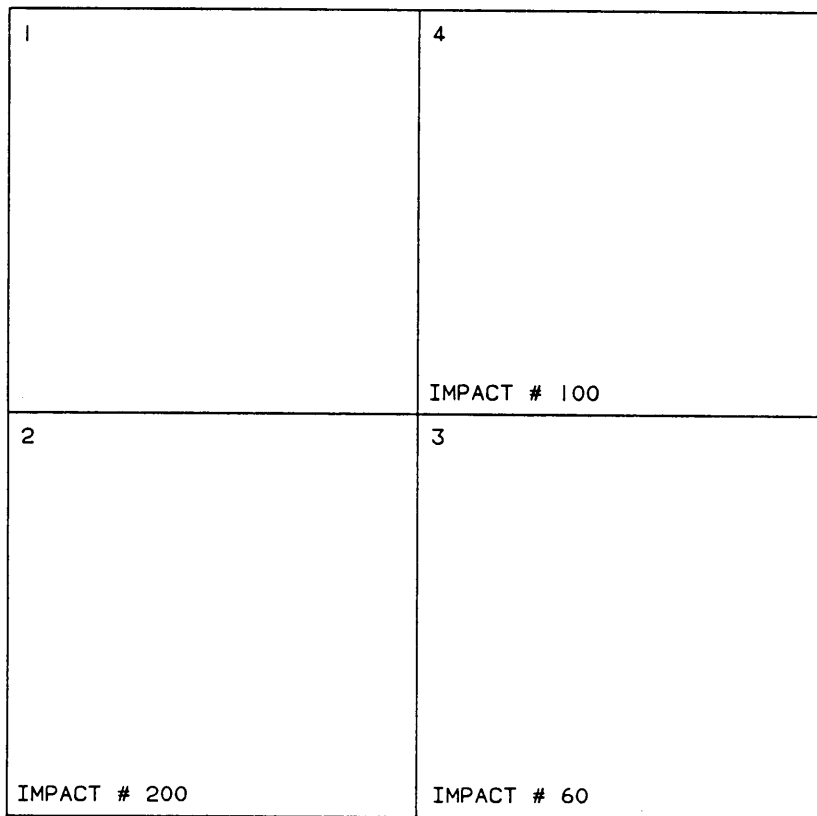Figure 6.   Plan of specimen GREP-1 showing damage locations.

Figure 7. Plan of specimen GREP-2 showing impacted regions.

The carbon-carbon specimens used were 3″ X 3″ and about 3/16 inch thick. One of the specimens was coated with an additional layer of carbon. This was sufficient to alter the values of AUF. Digitized waveform data were recorded at 22 different locations on each specimen.

The specimen GREP-1 was a unidirectional laminate, 12″ X 12″ and about 1/12 inch thick. This laminate was divided into four regions and flaws were introduced in three of these. A one inch crack was introduced in region two by cutting the fibers of the fourth layer from the top layer. A one inch square delamination was introduced into region three by using teflon inserts between the third and fourth layers. A half inch crack and a half inch square delamination were introduced in region four. Region one was referred to as plain region as no flaws were simulated in this region. Digitized waveform data were then recorded, with both the transducers lined along the fiber direction at forty different locations in each region. The recorded information were later used for spectral analysis.

The specimen GREP-2 had a layup of $[0,90_3]_s$ and had a dimension of 11.75″ X 11.75″ . The ultrasonic C-scan of this specimen after it had been fabricated is shown in figure(19). As in GREP-1, this specimen was also divided into four regions. Impact tests were carried out on three regions. An approach taken by Williams et. al. [20] to detect impact damage in composites by AU technique has been adopted. The first region was kept in the manufactured state and is considered the good portion. The impact tests are described briefly hereunder:

Figure(8) shows the impact setup used for regions two and four. Figure(9) indicates the type of support conditions of the specimen for the two regions. Figure(10) shows the impact setup used for region three. In this case a cylindrical block with rounded edges and made of aluminum was used. This block weighed 3.347 lbs and was dropped from a height of 6.0 inches. The number of impacts were sixty. A steel ball

weighing 3/32 lb was dropped from a height of 5.25 feet. The impact energy generated in these cases were 1.6735 and 0.49 lb-ft for regions two and four respectively. Region two was subjected to two hundred impacts and region four was subjected to one hundred impacts.

Figure(11) and figure(12) show the time/voltage and frequency spectra of region 1 of GREP-2. Figure(13) and figure(14) show the time/voltage and frequency spectra of region 2 of GREP-2. Figure(15) and figure(16) show the time/voltage and frequency spectra of region 3 of GREP-2. Figure(17) and figure(18) show the time/voltage and frequency spectra of region 4 of GREP-2. It can be seen that the amplitude of both the time/voltage and frequency spectra decrease with the damaged condition of the regions 1,2,4 and 3 respectively.

Figure(20) shows an ultrasonic C-scan of the specimen after impacting and the extent of damage caused can be seen. The entire exercise was performed to introduce defects randomly in each region and to compare them with the standard region by performing statistical tests on the AUF values obtained. Digitized waveform data were then recorded at fifty different locations in each region.

4.1.2   Spectrum Analysis and AUF calculation :

Spectrum analysis is performed on the digitized data. Software was developed for this purpose. This software can be classified into the following sections.

- Reading the parameters and the digitized data and converting to Time/Voltage readings.

ELECTROMAGNET

STEEL BALL

63"
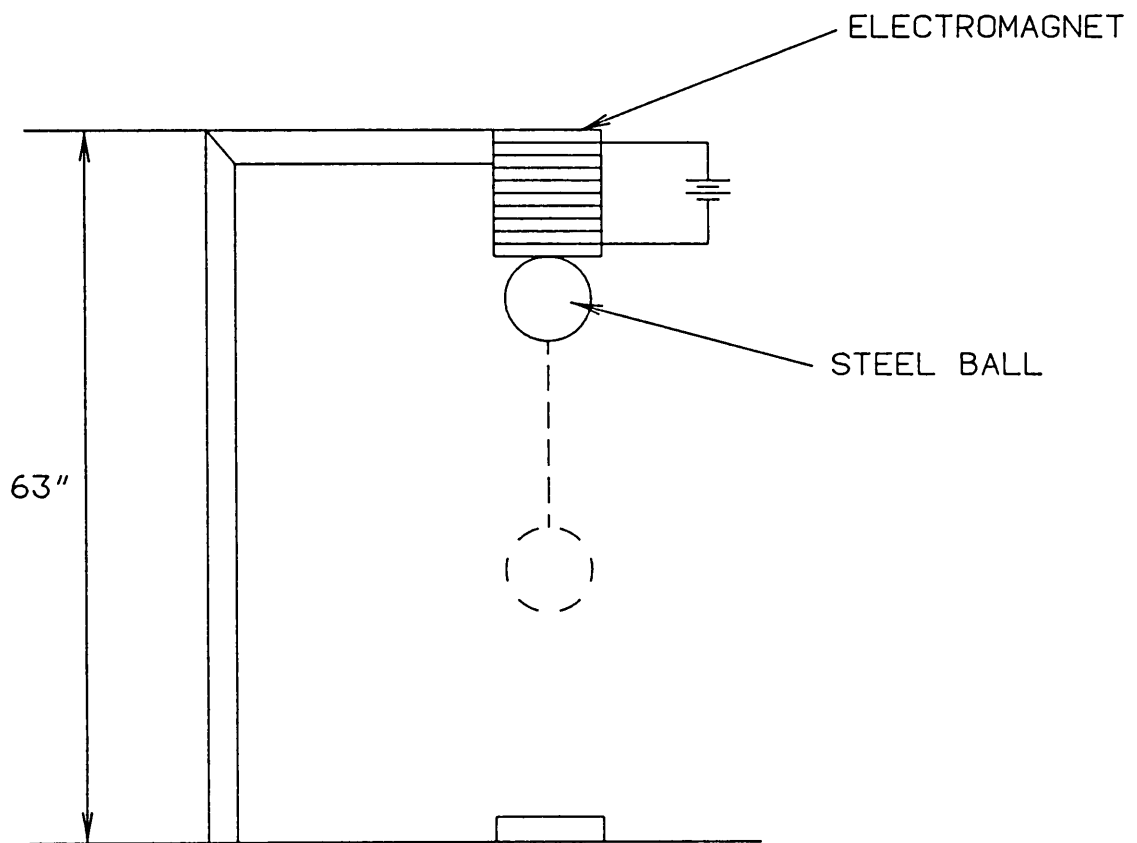
Figure 8.   Impact setup for regions 2 and 4.
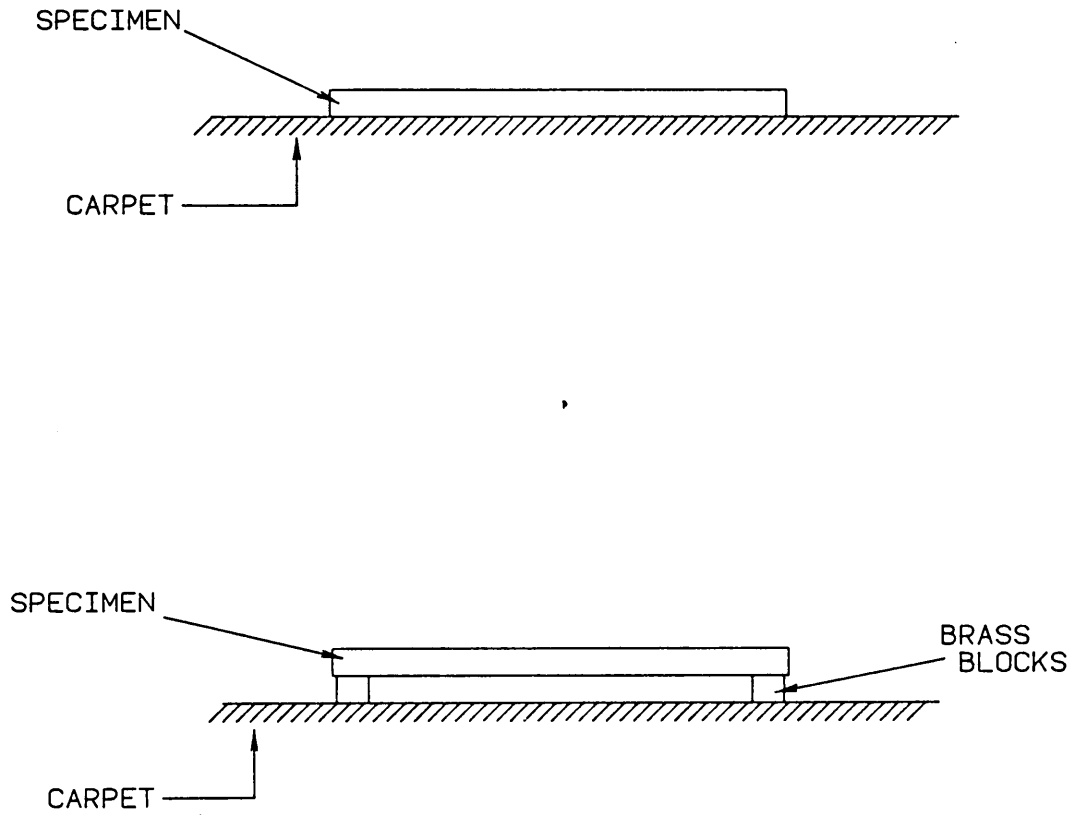
Figure 9.   Support conditions for impacting region 2 and 4 respectively.
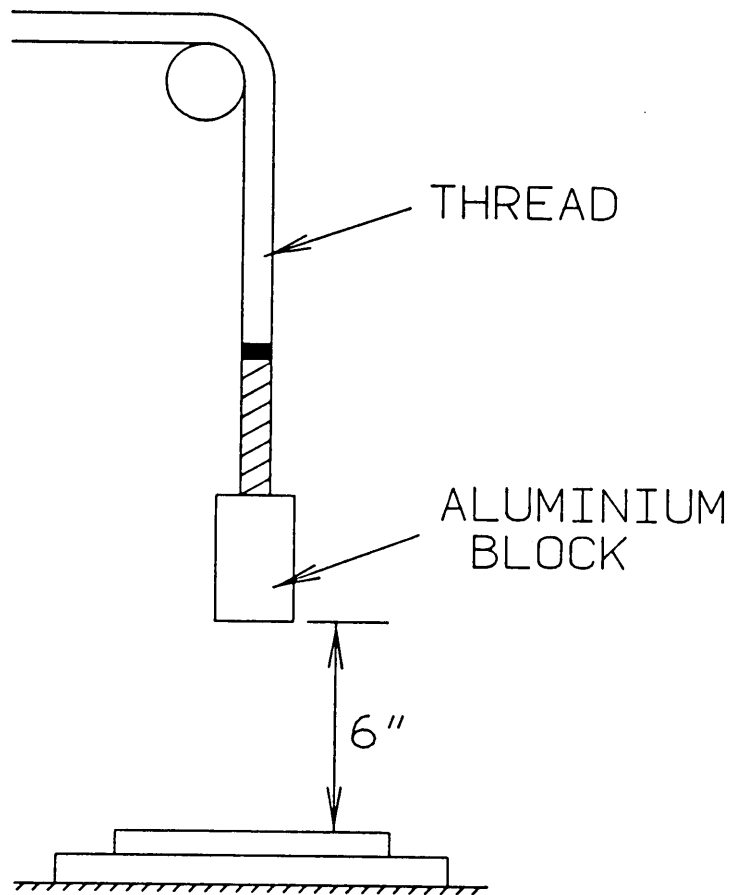
Figure 10. Impact setup for region 3.
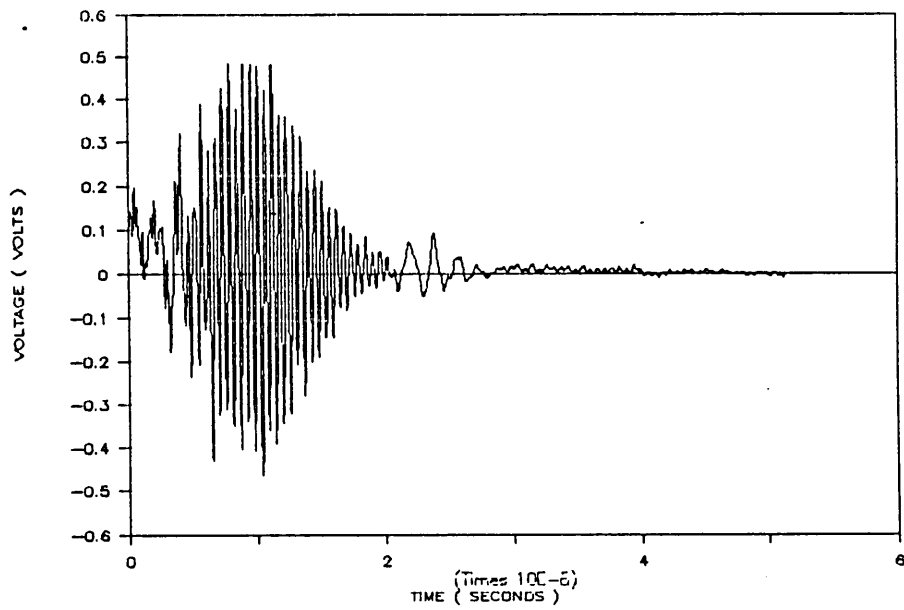
Figure 11. Time/voltage plot for region 1 of GREP-2
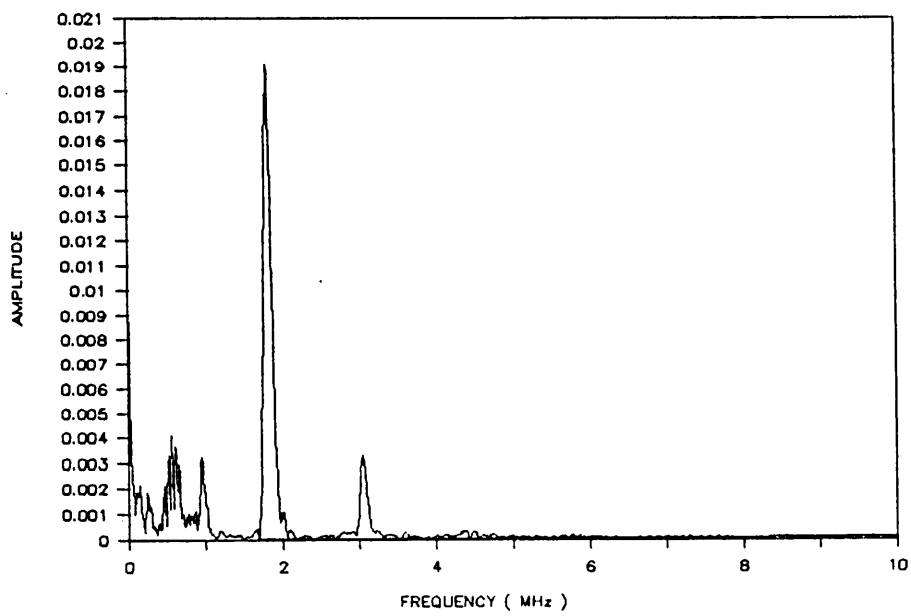
Figure 12. Frequency spectrum for region 1 of GREP-2
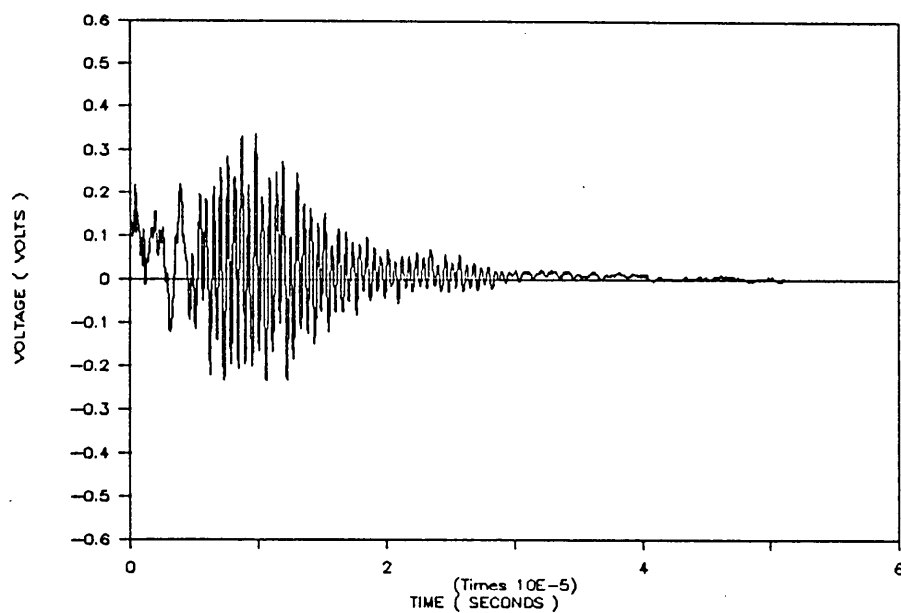
Figure 13. Time/voltage plot for region 2 of GREP-2
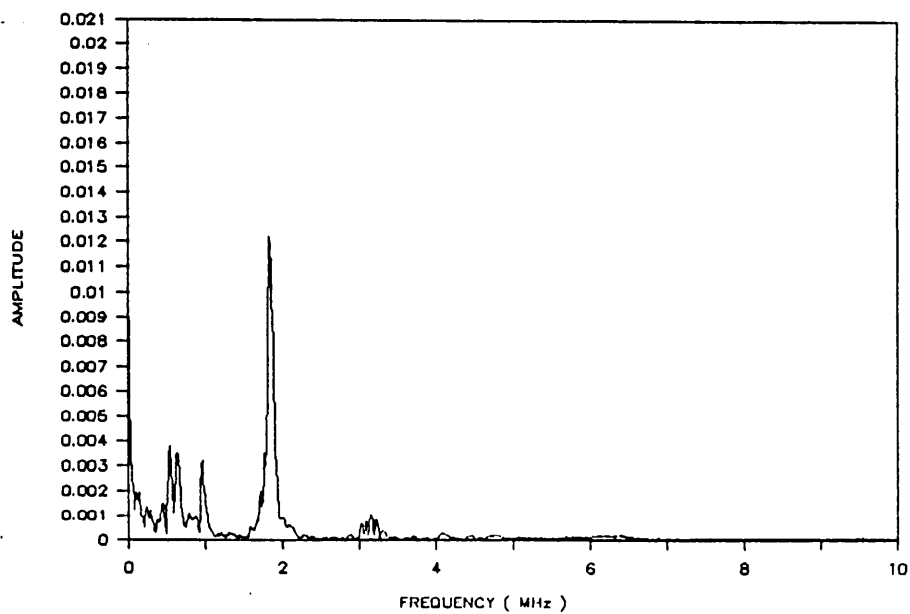
Figure 14. Frequency spectrum for region 2 of GREP-2
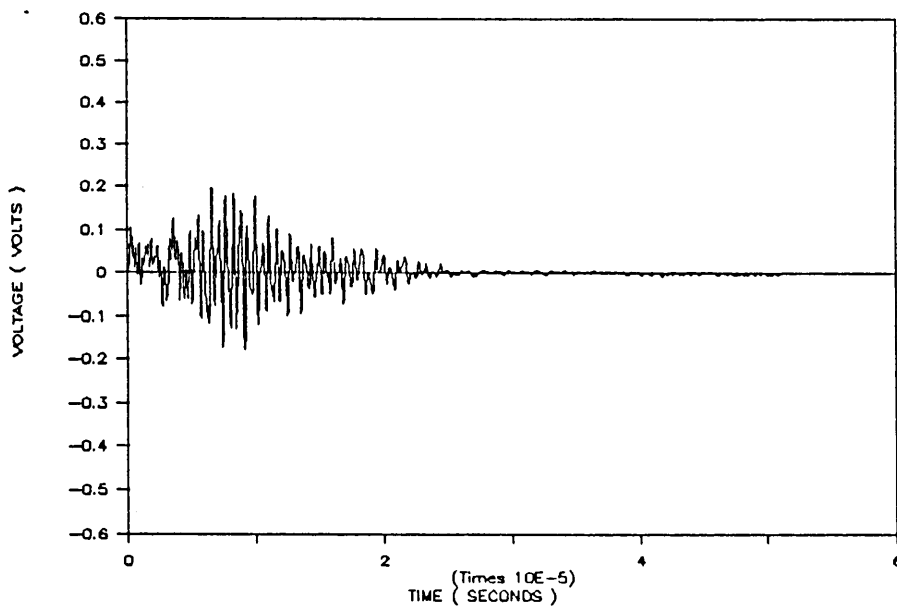
Figure 15. Time/voltage plot for region 3 of GREP-2
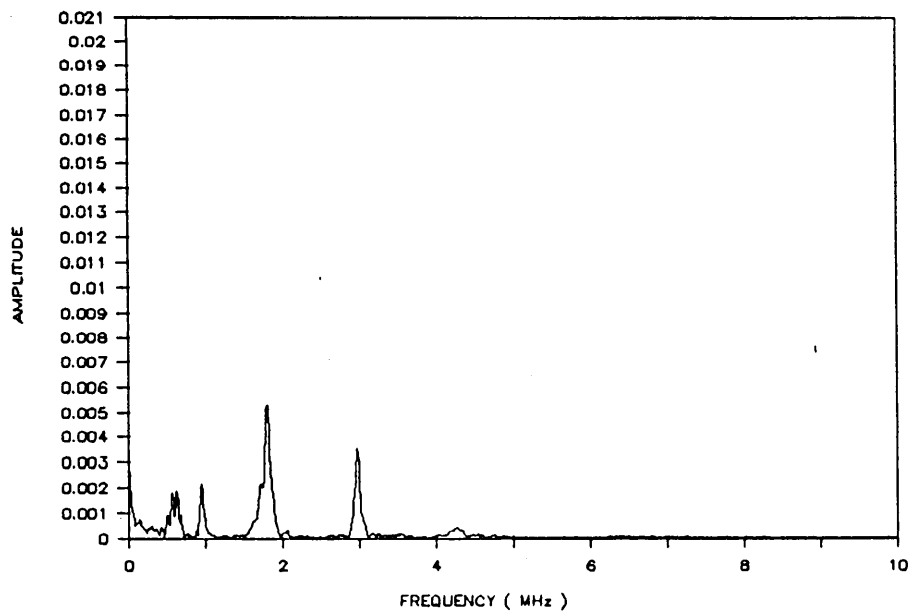
Figure 16. Frequency spectrum for region 3 of GREP-2
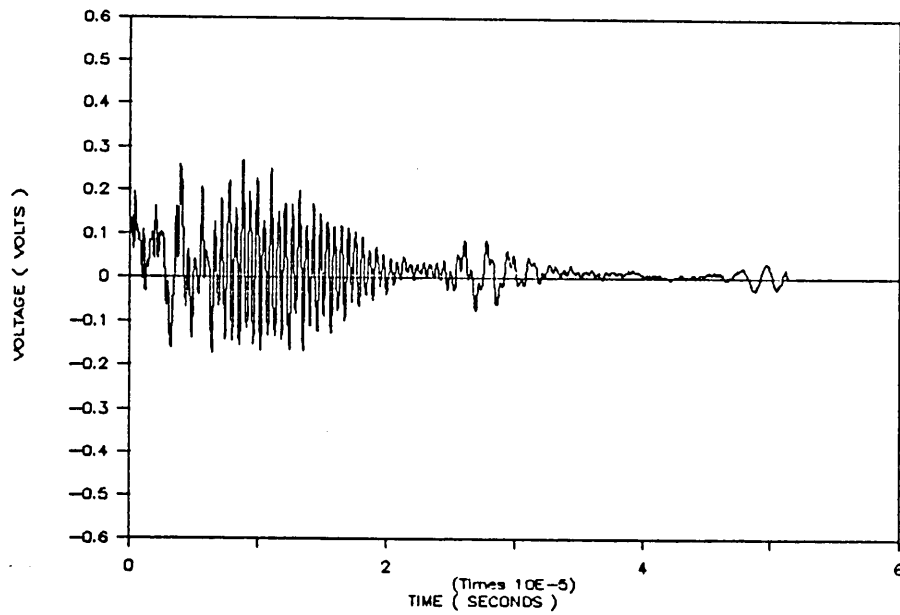
Figure 17. Time/voltage plot for region 4 of GREP-2
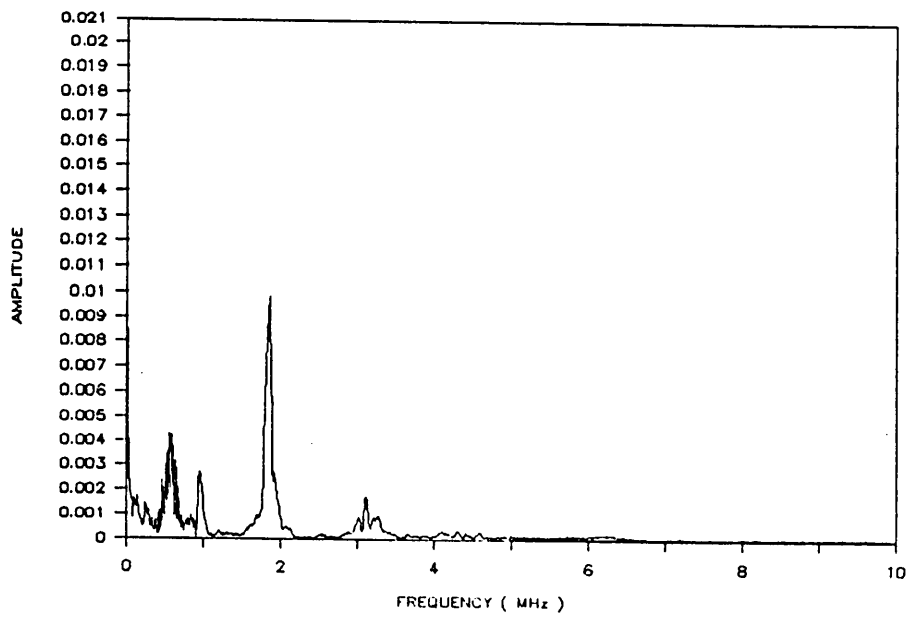
Figure 18. Frequency spectrum for region 4 of GREP-2
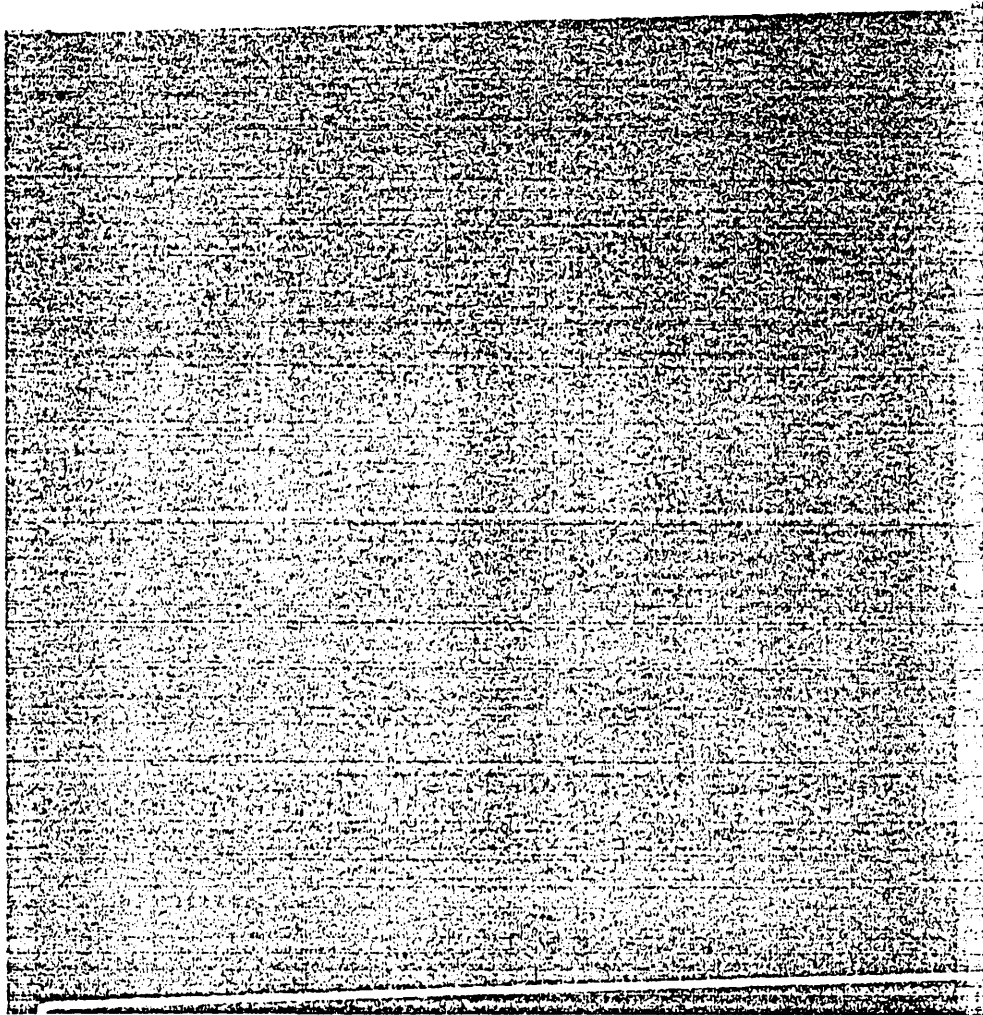
Figure 19. Ultrasonic C-scan of GREP-2 before impact.
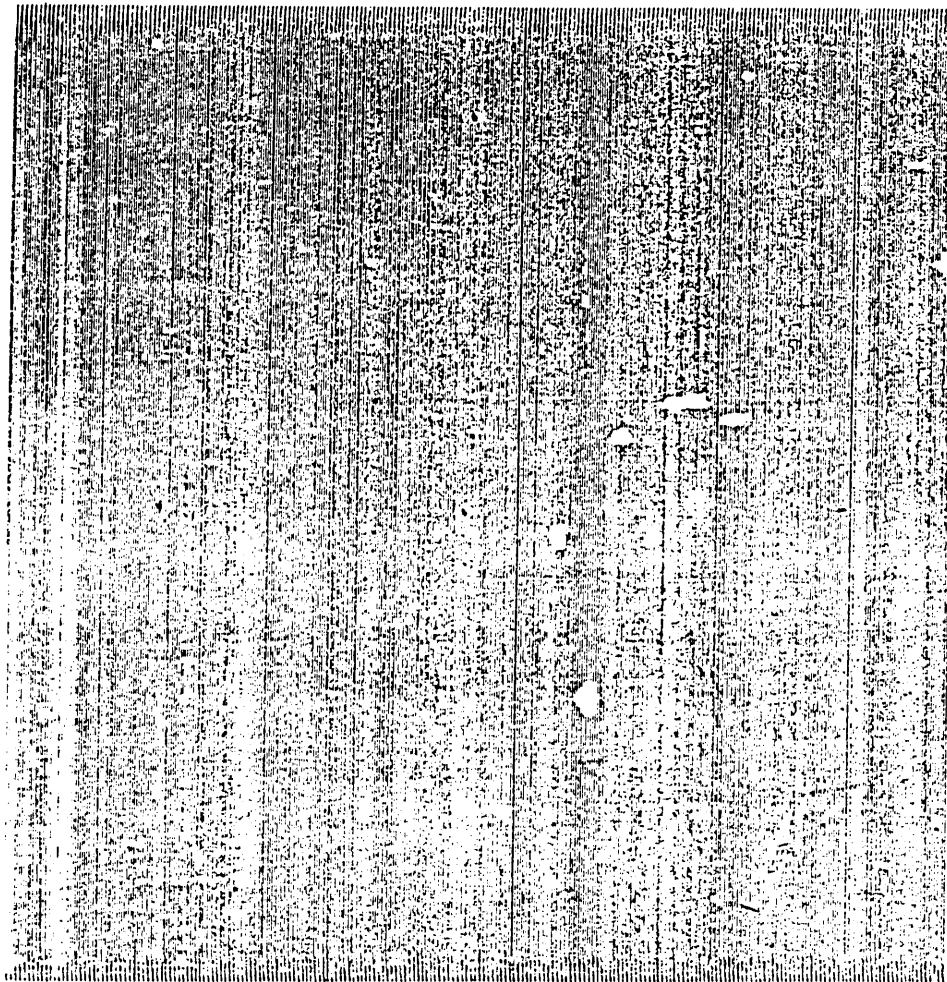
Figure 20.   Ultrasonic C-scan of GREP-2 after impact.

- Plotting Voltage vs Time : A subroutine PLOTS.FOR written by Becker [21] has been used for this purpose.

- Gating - In order to gate the digitized data and perform spectral analysis on the window, the values before and after the gate intervals are set to zero. The gate set points can be read via a terminal.

- Fast Fourier Transform (FFT) - The Voltage/Time data is then converted to 2^n data points in order perform FFT. The FFT is then performed according to a routine given in Newland [22]. The output so obtained after performing FFT is a complex array, from which amplitude is calculated.

- Plotting Amplitude vs Frequency - This is done by calculating the amplitude from the output of the FFT routine. The plotting is done using Becker's [21] routine.

- Calculation of AUF is then accomplished according to the equation [5] in chapter 3.

The various values of AUF obtained are then written to a file which can be used for statistical analysis.

The listing of the programs used have been included in the appendix. To use this program for calculating the AUF, all the data files that have to be processed should be in a batch file GURU.BAT . The AUF values are written to the file SWF0.DAT .

4.1.3 Statistical Testing :

In order to perform statistical analysis on the stored AUF values a program was written which is outlined below:

- Modify the AUF values: The AUF values which were stored using the AUFACT.FOR program can be modified using a linear relation as given by equation [19].

$$AUF_m = (AUF_a - C)N \qquad [19]$$

where

AUF_m is the modified AUF

AUF_a is the actual AUF

C, N are the arbitrary constants.

This is done to keep the parameters of the Beta distribution α and β within a certain range. The modified values are then subjected to statistical tests and various parameters are calculated.

- Calculate the mean and the variance. The mean of the AUF_m is calculated according to the relation.

$$\mu = \frac{1}{N} \sum_{i=1}^{N} AUF_m \qquad [20]$$

The variance is calculated according to the equation

$$\sigma^2 = \frac{(\Sigma AUF_m^2 - n\mu^2)}{(n - 1)} \qquad [21]$$

- Calculate parameters of Beta distribution : Once the mean and the variance of the modified AUF values are calculated the parameters of the beta distribution α and β are evaluated using the equations [9] and [10] or equations [11] and [12] as discussed in chapter three.

- Cumulative distribution function: The values α and β together with probability P are input into a subroutine MDBETI [23]. MDBETI computes the values of AUF such that the probability of a random variable having beta distribution being less than or equal to AUF value is P. Consequently one can find the probability P that a random variable having beta distribution with parameter α and β, is less than or equal to AUF. Having got the AUF values at various probabilities P, the plot of cumulative distribution function is then obtained.

In order to check the validity of the distribution, goodness of fitness tests were performed. A K-S goodness of fit test is used for this purpose. The method is outlined earlier in chapter 3.

Finally a simulation was performed by altering the parameters of the Beta distribution. The values of α and β are varied and the different combinations used are given below. This was done to observe the trend in change of the CDF curves. Thus one can identify the change in pattern of parameters from good and bad specimens. The following were the combinations of the α and β :

1. constant α and increasing β
2. constant α and decreasing β
3. increasing α and constant β
4. decreasing α and constant β
5. increasing α and decreasing β
6. decreasing α and decreasing β
7. increasing α and increasing β

The listings of the program and the subroutine used are given in the appendix.

Finally a hypothesis test was performed considering the means of the specimen GREP-2. The t-test statistic was calculated in each case.

5.0   Results and Discussions

The results of the statistical analysis of the AUF responses are shown in Table (1) and Table (2). The Kolmogorov Smirnov test indicates that Beta distribution provides a very good fit to the observed data. This is reflected by the values of D_n and D_{crit} in table 1, wherein the values of the maximum discrepancy D_n are less than D_{crit} at a significance level of 0.20 for both carbon and GREP-1 specimens. Therefore it appears that the Beta distribution is a representative model of the AUF response. Further, the particular Beta distribution models that represent the AUF response of data from different types of specimens/regions are clearly distinct. This is shown in figure (21) which is the plot of cumulative distribution function (CDF) against the statistical AUF and highlights the difference between coated and uncoated specimens.

Figure (22) is a plot of CDF vs AUF(statistical) which indicates the difference in the AUF response of specimen GREP-1 after statistical treatment. It is clearly seen that the Beta model clearly distinguishes between the plain region and the defect induced regions. These damaged regions which could be thought of as defects which creep in during fabrication stages can thus be clearly identified by the CDF plots by referring

them to a standard CDF curve. Further, the acceptable level of quality can be fixed based on these and hence the accept/reject criterion.

Figure (23) is also a plot of CDF vs AUF(statistical) which indicates the differences in the response between plain and impacted regions of the specimen GREP-2. It is observed that region 3 has been affected more than region 2 and region 4 after the impact tests. The various levels of impact can be clearly identified and thus these damages can be thought of as being induced during service. An acceptable level of deterioration which can be based on reduction in stiffness of the material can be fixed and thus one can continuously evaluate the quality of composite product even during service.

Figure (24) through Figure (30) show the plots of the cumulative distribution function for simulated values of α and β Note that the value of $\alpha = 18$ and $\beta = 24$ is taken as a reference standard and the changes in α and β are relative to this. It can be concluded from these figures that in order to maintain quality of a specimen the α values should be constant or increase whereas the β values should be constant or decrease. Thus by observing the α and β of a particular batch, various damage levels can be simulated by varying the values of α and β.

As discussed earlier a hypothesis test can be performed and the t-test statistic has been found for each of the means of specimen GREP-2. The various t-test statistic values are listed in Table(2). Note that these values can be compared with the critical value of t-test statistic for each particular region/specimen at a particular significance level. One of the methods of fixing the critical value is as follows. For a particular batch of specimens appropriate tests are conducted to evaluate the strength or stiffness of the material. Then based on the strength or stiffness requirements of the material for a particular application, if the above specimens prove satisfactory, AUF values are calculated from the same batch of specimens. Then as discussed earlier the t-test statistic

Table 1.   Parameters of the Beta distribution for carbon and GREP-1 specimens.

	Mean (μ)(modified)	Variance $\sigma^2 10^{-2}$	Alpha α	Beta β	D_n	D_{crit}†
Carbon						
Uncoated	0.3139	1.0340	11.56	15.16	0.0454	0.2281
Coated	0.4325	0.8850	16.60	25.90	0.0773	0.2281
GREP-1						
Region 1	0.4211	0.5568	18.02	24.76	0.0750	0.1691
Region 2	0.4097	0.4783	20.31	29.25	0.1000	0.1691
Region 3	0.3905	0.5472	16.60	25.90	0.0750	0.1691
Region 4	0.3627	0.4761	17.25	30.30	0.1000	0.1691

† Value taken from statistical tables for significance level of 0.2 and number of AUF observations n.

Table 2. Parameters of the Beta distribution for GREP-2 specimens.

	Mean (μ)	Variance $\sigma^2 x 10^{-2}$	Alpha α	Beta β	t-test statistic t†
Region 1	0.6726	0.4497	32.26	15.70	2.38
Region 2	0.6494	0.4881	29.64	16.00	-0.06
Region 3	0.5627	0.2381	57.60	47.75	-12.60
Region 4	0.5874	0.3091	45.46	31.93	-7.96

† t-test statistic is calculated based on $\mu = 0.6500$.
   t_{crit} is obtained from tables at significance level of 0.1
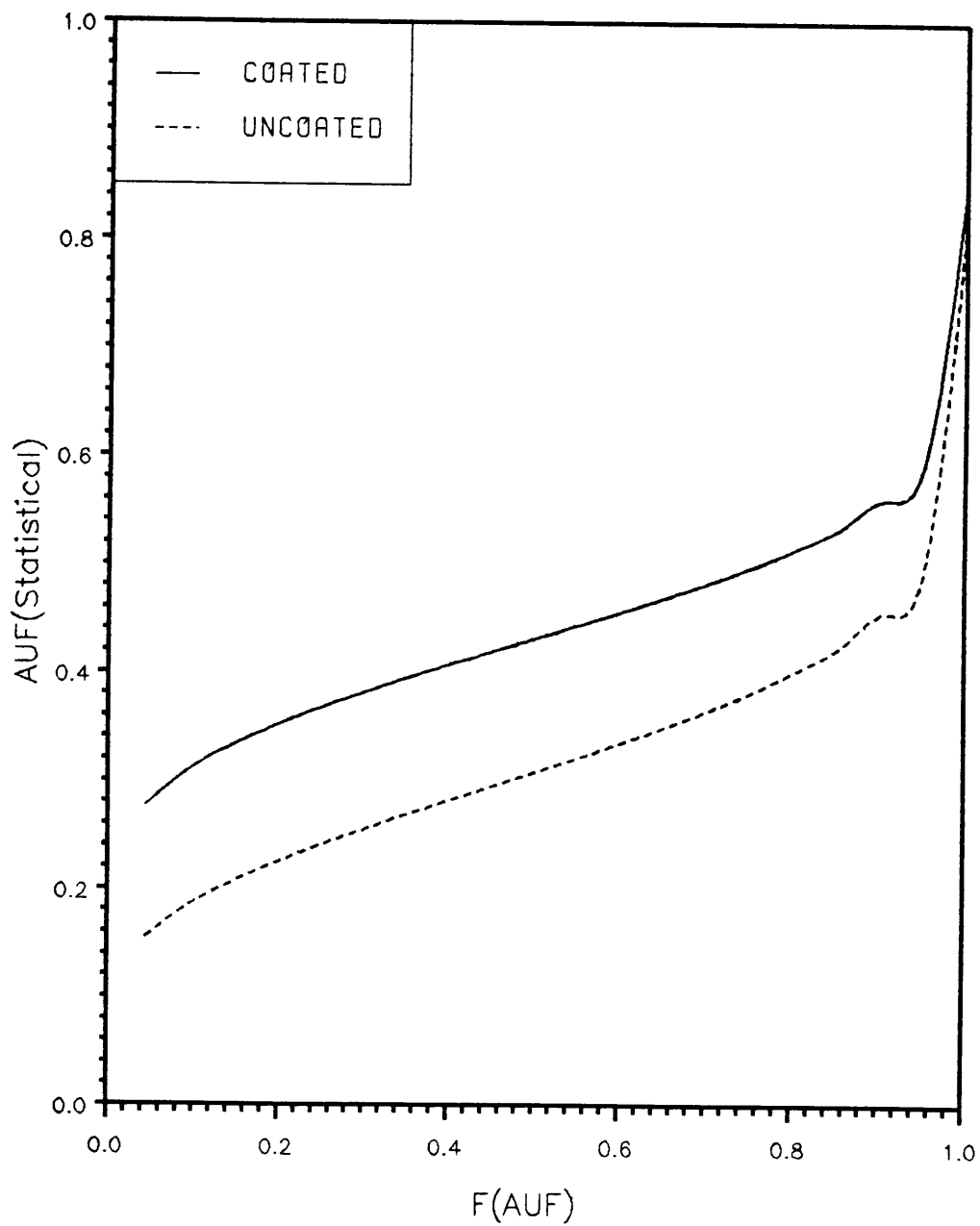
Figure 21. Plot of Cumulative distribution function indicating the difference between the two carbon specimens.
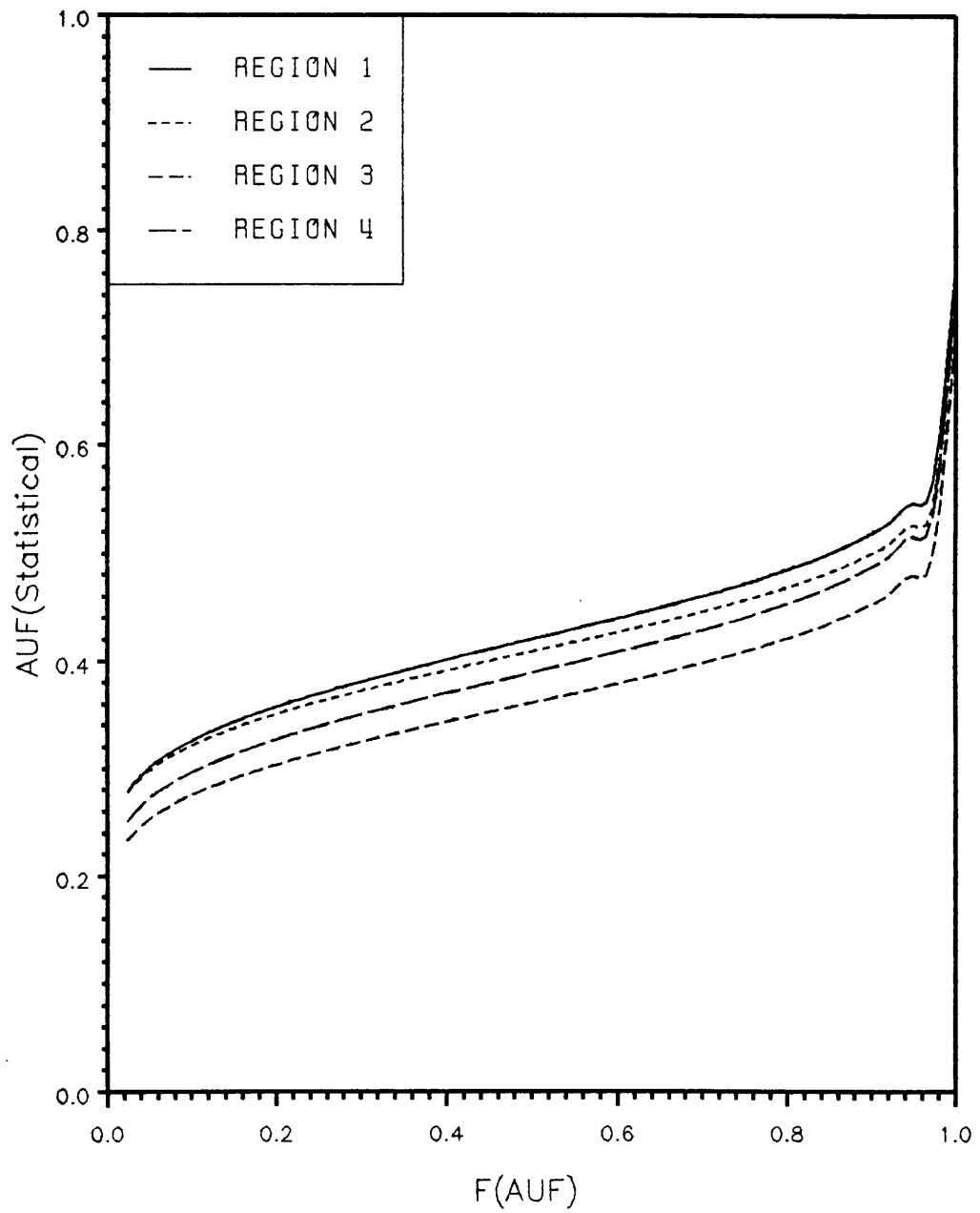
Figure 22. Plot of Cumulative distribution function indicating the difference between the different regions of GREP-1.
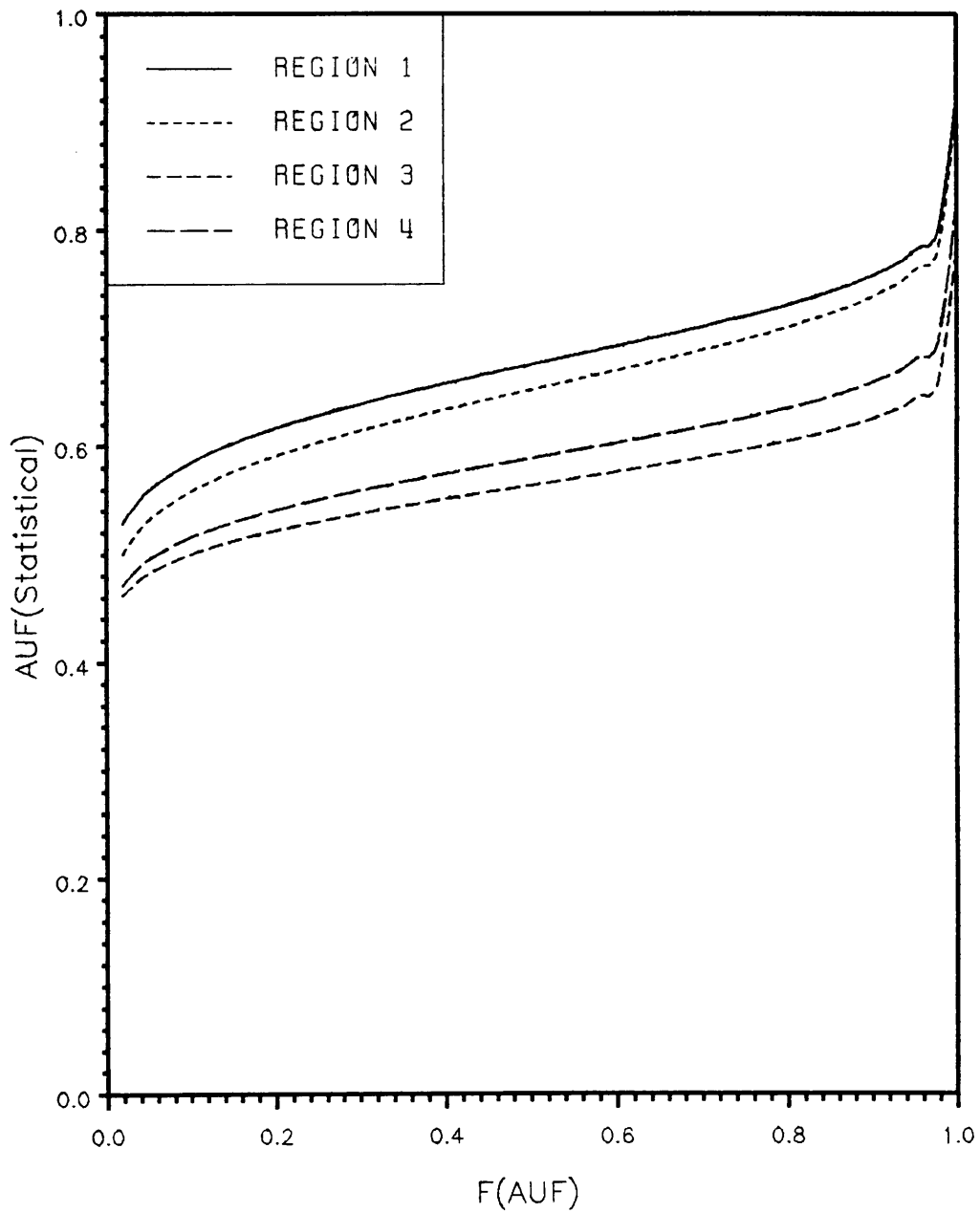
Figure 23. Plot of Cumulative distribution function indicating the difference between the different regions of GREP-2.
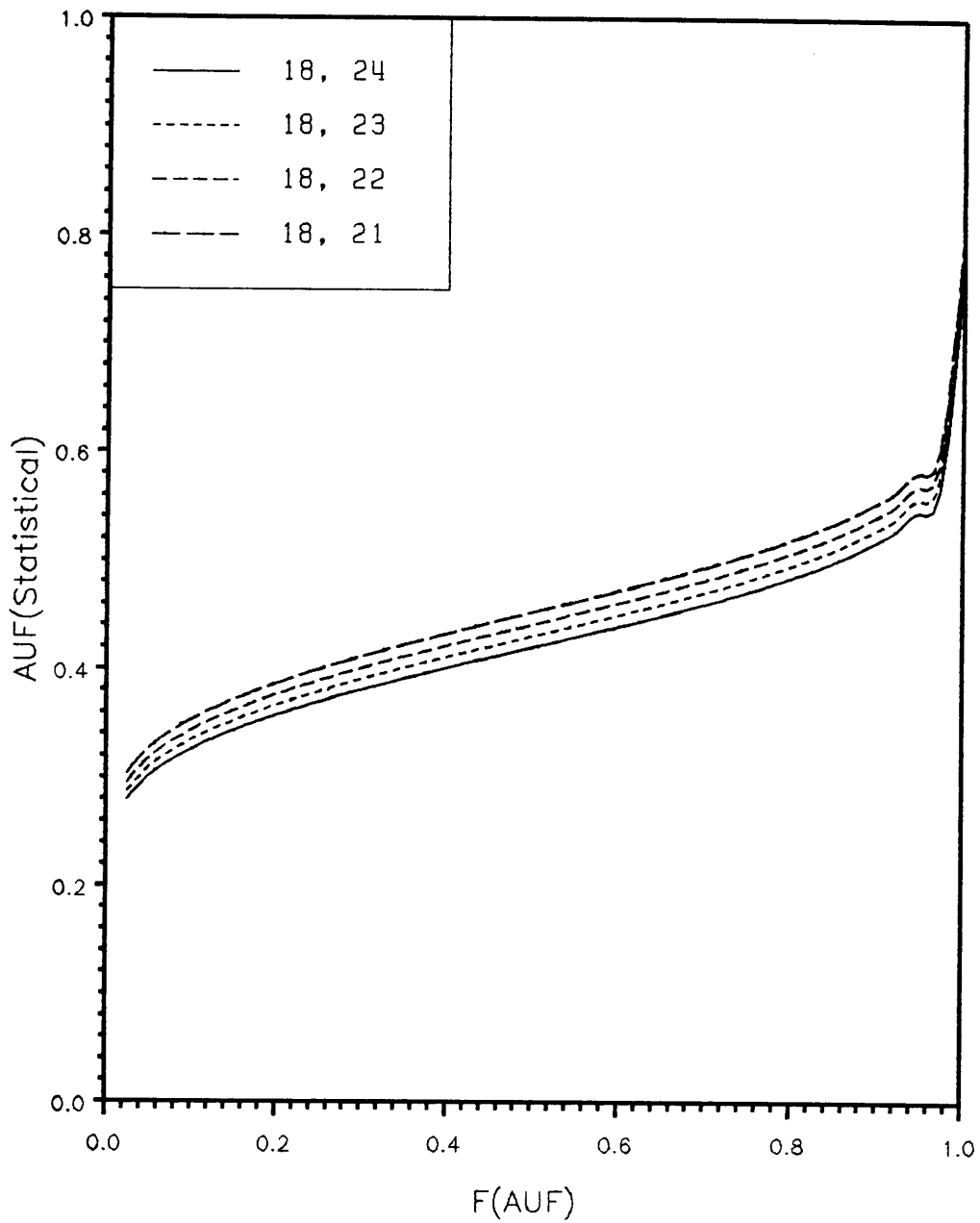
Figure 24. Plot of Cumulative distribution function for constant α and decreasing β.
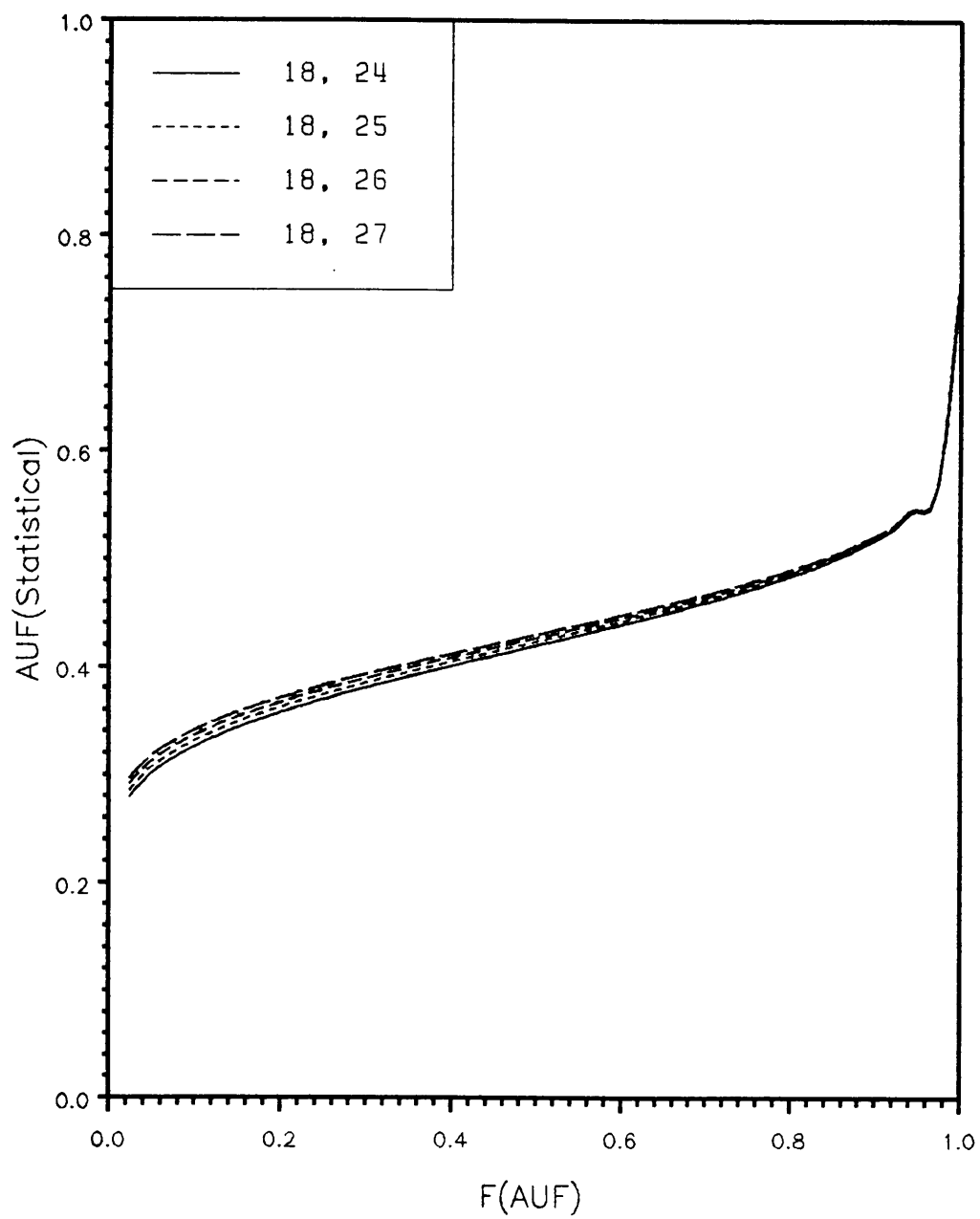
Figure 25.   Plot of Cumulative distribution function for constant α and increasing β.
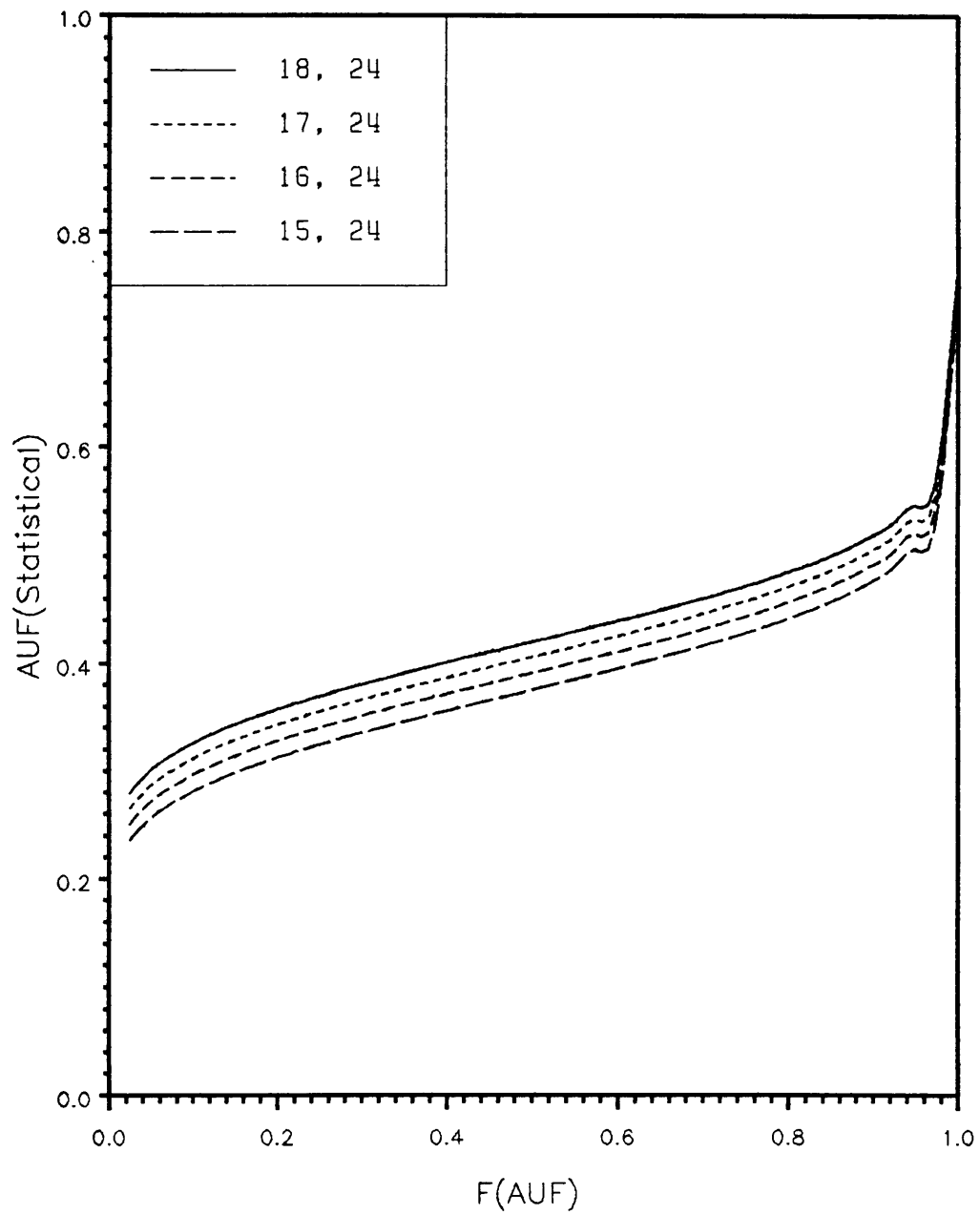
Figure 26. Plot of Cumulative distribution function for decreasing α and constant β.
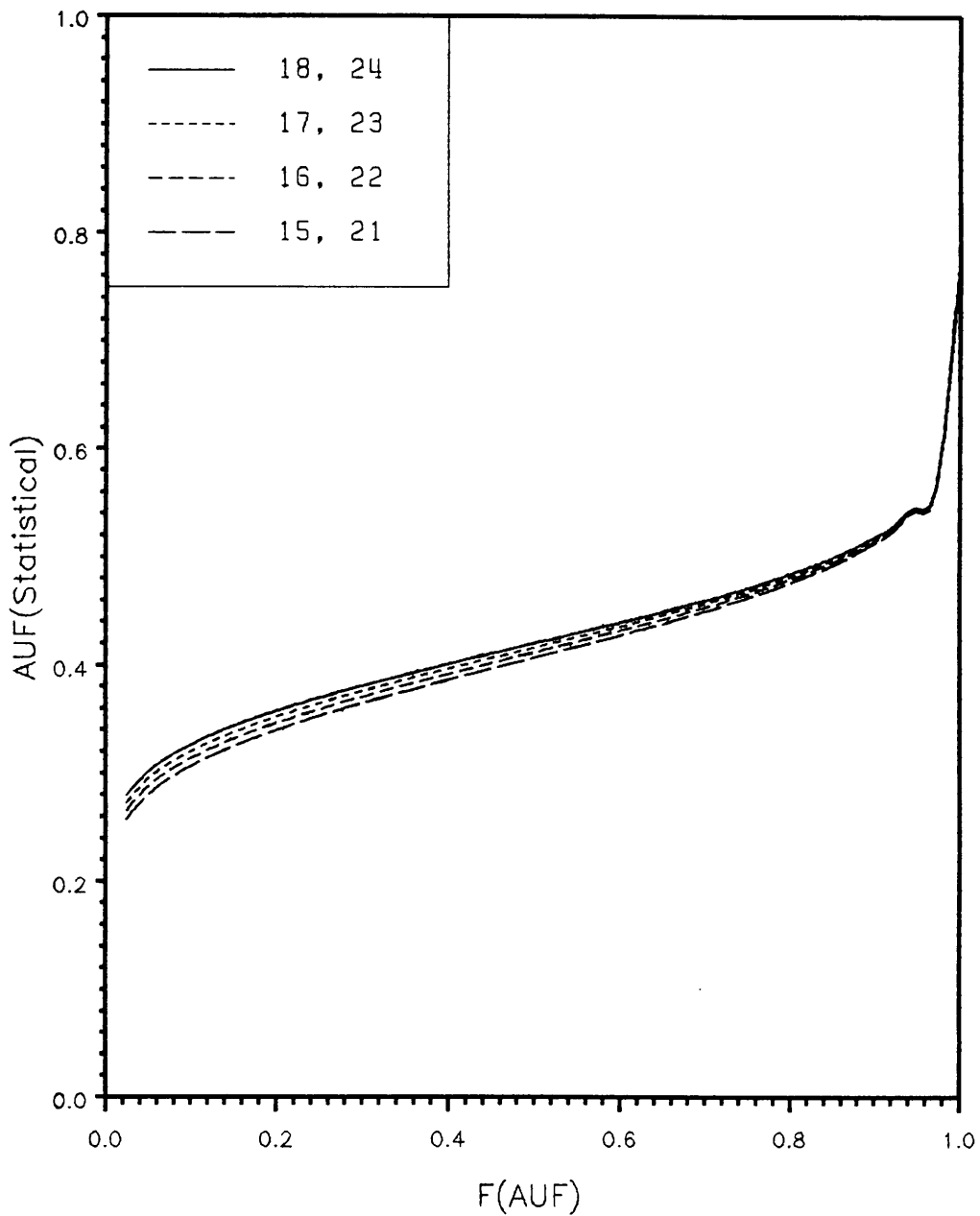
Figure 27. Plot of Cumulative distribution function for decreasing α and decreasing β.
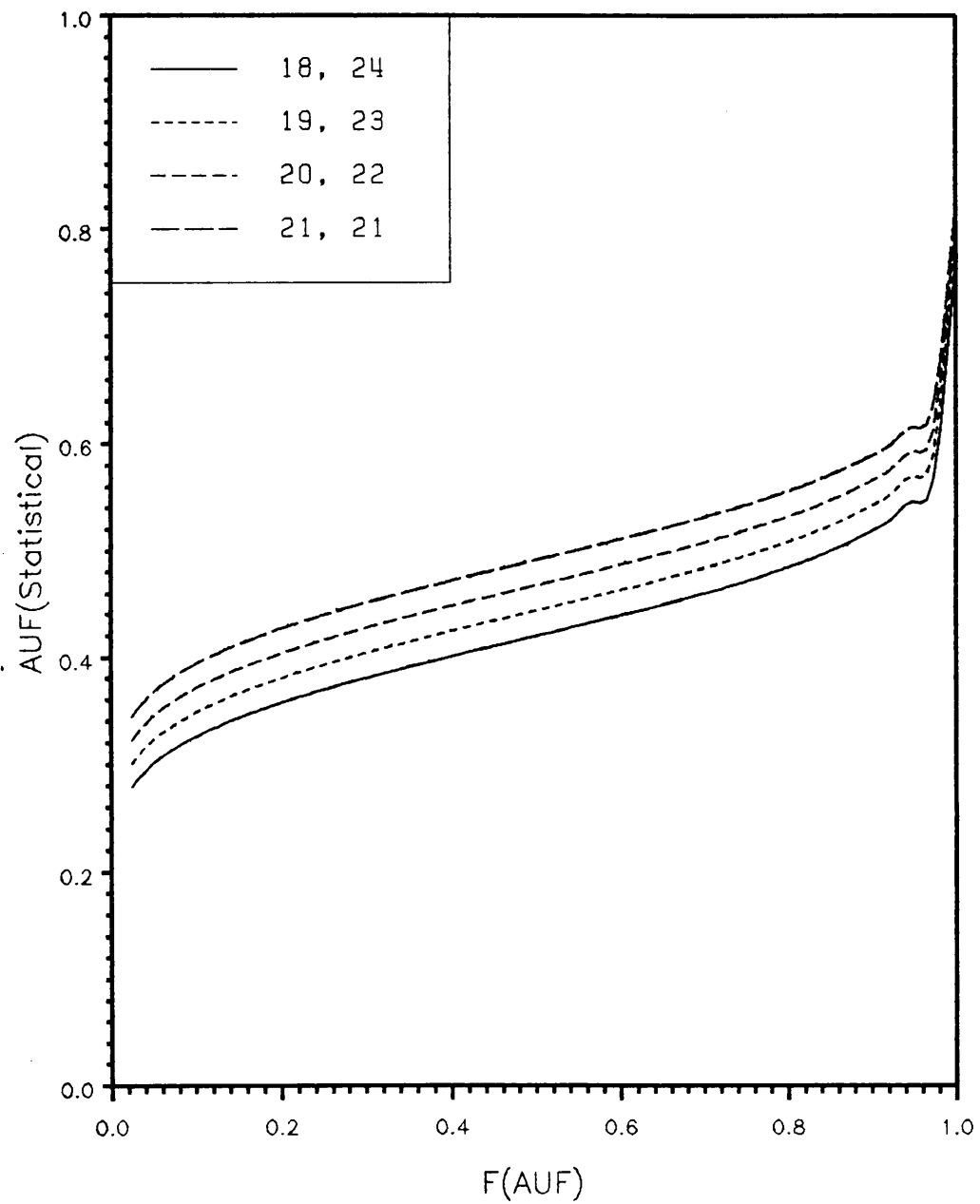
Figure 28. Plot of Cumulative distribution function for increasing α and decreasing β.
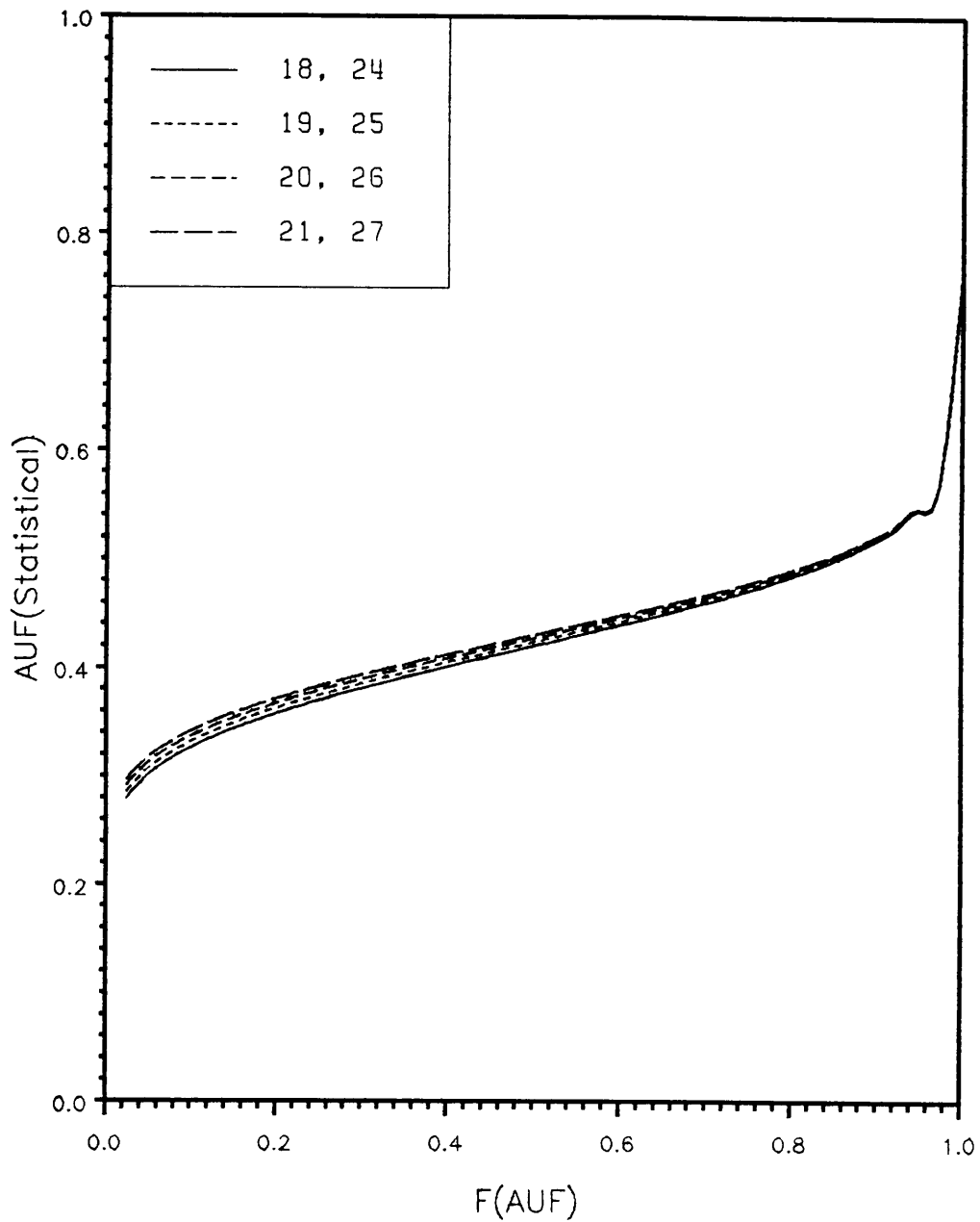
Figure 29. Plot of Cumulative distribution function for increasing α and increasing
β.

can be evaluated. This can be designated as the critical t-test statistic. Comparisons of this critical value with that of t-test statistic of other specimens of the same batch can serve as one of the methods for an accept/reject criterion.

5.1.1 CONCLUSIONS

The following are the conclusions of this study:

- The Acousto-Ultrasonic Factor is a useful parameter which can be used for characterizing composites.
- The AUF response from a composite material follows a Beta distribution.
- A lower bound on the cumulative distribution curve is helpful for modelling an accept/reject criteria for monitoring quality of composites.
- A t-test statistic can be used as a short-cut method to evaluate the quality of a particular specimen/region.

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APPENDIX

The following programs were used for the calculation of AUF and for performing statistical analysis.

- AUFACT.FOR: This program reads the digitized data recorded by PCDAS and calculates the AUF value. The following are the subroutines encountered.
  - PLOTS.FOR - A subroutine used for plotting.
  - FASTFT.FOR - A subroutine used for performing fast fourier transform.
- STATAUF.FOR: This program performs statistical analysis on the AUF values. The program calculates the mean, the variance, the parameter of the Beta distribution α and β. Subroutine used is,
  - MDBETI - A IMSL subroutine for calculating the AUF values at various percentage points.

The listings of the programs and subroutines follow.

```
C*********************************************************************
C
C  AUFACT.FOR - PROGRAM TO CALCULATE ACOUSTO-ULTRASONIC FACTOR (AUF).
C
C*********************************************************************
C
       IMPLICIT REAL*4(A-H,O-Z)
       INTEGER VT,A,GLEN,IER,PROMP1,PROMP2,PROMP3,NGLEN,NGEND,NGST,GLEN1
       COMPLEX AC(16400)
       DIMENSION A(16),VT(256,16),VOLTS(4100,1),TIME(4100),AR(16400)
      1 ,AI(16400),AMP(16400,1),FREQ(16400)
       CHARACTER*20 FNAME,FLNAME,XLBL,YLBL,XLABL,YLABL,FINAME,B
C
C*********************************************************************
C
C                        SECTION 1
C
C*********************************************************************
C
C      CREATE A BATCH FILE TO PROCESS DIGITIZED DATA FROM PCDAS (INPUT).
C      IN THIS PROGRAM GURU.BAT IS THE BATCH FILE WHICH HAS ALL THE
C      DATA FILES TO BE PROCESSED. ONE CAN CHANGE THE BATCH FILE NAME
C      BY CHANGING THE VARIABLE FNAME.
C
C      THE FOLLOWING VARIABLES ARE READ FROM THE INPUT FILE:
C
C      GSTART  = THIS IS THE GATE START INFORMATION.
C      SRATE   = THIS IS THE SAMPLING RATE INFORMATION.
C      VT(J,K) = DIGITIZED DATA POINTS READ AS AN ARRAY (MAXIMUM = 4096)
C      NGLEN   = GATE LENGTH CALCULATED FROM THE NUMBER OF DATA POINTS
C                RECORDED.
C
C*********************************************************************
       FNAME = 'GURU.BAT'
       OPEN(UNIT=7,FILE=FNAME)
       OPEN(UNIT=9,FILE='SWFO.DAT')
  10   READ(7,*,END = 120) FLNAME
       OPEN(UNIT=8,FILE=FLNAME)
       READ(8,*)
       READ(8,20) GSTART
  20   FORMAT(40X,F8.3)
       READ(8,30)SRATE
  30   FORMAT(19X,F8.3)
       DO 40 I = 1,13
       READ(8,*)
  40   CONTINUE
       J=1
  50   READ(8,*,END=60)(VT(J,K),K=1,16)
       J = J+1
       GOTO 50
```

```
      60    NGLEN = ((J-1)*16+K)
C*********************************************************************
C
C                              SECTION 2
C
C*********************************************************************
C
C        THIS SECTION CONVERTS THE DATA POINTS READ TO ACTUAL VOLTAGE.
C        TIME IS COMPUTED USING SAMPLING RATE AND GATE LENGTH. A PLOT OF
C        VOLTAGE VS TIME CAN BE OBTAINED. THE VOLTAGE AND TIME DATA CAN
C        BE STORED AS A SEPARATE FILE.
C
C        VARIABLES ENCOUNTERED:
C        VOLTS(M,1)  = VOLTAGE EQUIVALENTS OF THE INPUT DATA POINTS.
C
C        SUBROUTINES CALLED:
C        PLOTS.FOR
C        SCRNQQ.FOR ( LINK TO GRAPHS.LIB)
C
C*********************************************************************
         J =1
      70   DO 80 K = 1,16
         M = ((J-1)*16+K)
         VOLTS(M,1) = VT(J,K)*0.5/128
      80   CONTINUE
         J = J+1
         IF(M.GT.NGLEN) GOTO  90
         GOTO 70
         OPEN(UNIT=12,FILE='VOLT.DAT')
      90   DO 101 I = 1,NGLEN
         TIME(I) = 1/(SRATE*1000000)*I
         WRITE(12,*) TIME(I),VOLTS(I,1)
     101   CONTINUE
         WRITE(*,*) 'DO YOU WANT A PLOT OF VOLTAGE VS TIME'
         WRITE(*,*) ' YES (1)  OR  NO (2) '
C         PROMP1 = 2
         READ(*,*) PROMP1
         IF (PROMP1.EQ.2) GOTO 205
         XLBL = 'TIME IN SEC'
         YLBL = 'VOLTS'
         CALL PLOTS(TIME,VOLTS,NGLEN,NGLEN,1,0,0,1,XLBL,YLBL,IER)
         WRITE(*,*) 'HIT 1 TO PROCEED'
         READ(*,*) DELAY
         CALL SCRNQQ(3)
C*********************************************************************
C
C                              SECTION  3
C
C*********************************************************************
C
```

```
C        THIS SECTION CONVERTS THE NUMBER OF DATA POINTS (OR GATE LENGTH)
C        TO THE NEAREST 2**M NUMBER OF POINTS.
C        NGLEN IS RESET AS GLEN, WHERE GLEN = 2**M IS NEW GATE LENGTH.
C        THIS IS DONE FOR FFT PURPOSES.
C
C*******************************************************************************
  205    IF (NGLEN.LT.512) THEN
         GLEN = 512
         ELSE
         GOTO 65
         ENDIF
   65     IF ((NGLEN.GT.512) .AND. (NGLEN .LT. 1024)) THEN
         GLEN = 1024
         ELSE
         GOTO 75
         ENDIF
   75    IF(NGLEN.GT.1024 .AND. NGLEN .LT. 2048) THEN
         GLEN = 2048
         ELSE
         GOTO 85
         ENDIF
   85    IF(NGLEN.GT.2048 .AND. NGLEN .LE. 4096) THEN
         GLEN = 4096
         ELSE
         GOTO 95
         ENDIF
C*******************************************************************************
C
C                            SECTION  4
C
C*******************************************************************************
C        THIS SECTION ADDS ZEROES TO THE VOLTAGE ARRAY BEYOND THE
C        RECORDED DATA POINTS TO MAKE THE NEW GATE LENGTH = 2**M.
C        GATING CAN ALSO BE DONE ON THE SIGNAL AND THIS GATED REGION
C        CAN BE PLOTTED OR USED LATER FOR PERFORMING FFT'S.
C
C        VARIABLES USED:
C        GSTART = GATE START TIME.
C        GSTIME = NEW GATE START TIME SPECIFIED BY THE USER.
C        GEND   = GATE END TIME.
C        GETIME = NEW GATE END TIME SPECIFIED BY THE USER.
C
C        SUBROUTINES CALLED:
C        PLOTS.FOR
C        SCRNQQ.FOR
C
C*******************************************************************************
   95    DO 105 I = NGLEN + 1,GLEN
         VOLTS(I,1) = 0.0
  105    CONTINUE
```

```
            WRITE(*,*) 'DO YOU WANT TO GATE THE SIGNAL'
            WRITE(*,*) ' YES(1) OR NO(2) '
C            PROMP4 = 2
            READ(*,*) PROMP4
            IF(PROMP4.EQ.2) GOTO 145
            WRITE(*,*) 'GATE STARTS FROM',GSTART,' MICRO SECONDS'
            WRITE(*,*) 'ENTER TIME > GATE START IN MICRO SECONDS'
            READ(*,*) GSTIME
            GEND = GLEN/(SRATE)
            WRITE(*,*) 'GATE ENDS AT',GEND, 'MICRO SECONDS'
            WRITE(*,*) 'ENTER TIME < GATE END IN MICRO SECONDS'
            READ(*,*) GETIME
            NGST = GSTIME*SRATE
            NGEND = GETIME*SRATE
            DO 115 I = 1,NGST
  115       VOLTS(I,1) = 0.0
            DO 125 I = NGEND,GLEN
  125       VOLTS(I,1) = 0.0
            DO 100 I = 1,GLEN
            TIME(I) = 1/(SRATE*1000000)*I
  100       CONTINUE
  175       WRITE(*,*) 'DO YOU WANT A PLOT OF VOLTAGE VS TIME'
            WRITE(*,*) ' YES (1)  OR  NO (2) '
            READ(*,*)  PROMP5
            IF (PROMP5.EQ.2) GOTO 145
            XLBL = 'TIME IN SEC'
            YLBL = 'VOLTS'
            CALL PLOTS(TIME,VOLTS,GLEN,GLEN,1,0,0,1,XLBL,YLBL,IER)
            WRITE(*,*) 'HIT 1 TO PROCEED'
            READ(*,*) DELAY
            CALL SCRNQQ(3)
C**********************************************************************
C
C                              SECTION 5
C
C**********************************************************************
C
C    THIS SECTION CALLS THE ROUTINE AND PERFORMS FFT ON THE TIME-VOLTAGE
C    DATA. THE AMPLITUDE IS THEN CALCULATED AND A PLOT OF AMPLITUDE
C    VS FREQUENCY CAN BE OBTAINED. THE AMP AND FREQ DATA CAN ALSO BE
C    STORED FOR FUTURE REFERENCES.
C
C    VARIABLES USED:
C    AC(I) = A COMPLEX ARRAY WHICH IS THE VOLTAGE DATA FOR INPUTING TO
C            THE FFT ROUTINE. THE OUTPUT IS ALSO A COMPLEX ARRAY AFTER
C            FFT.
C    AR(I) = REAL PART OF AC(I) AFTER THE FFT.
C    AC(I) = IMAGINARY PART OF AC(I) AFTER  THE FFT.
C    AMP(I,1) = AMPLITUDE.
C    FREQ(I)  = FREQUENCY.
```

```fortran
C
C     SUBROUTINES CALLED:
C     FFT.FOR
C     PLOTS.FOR
C     SCRNQQ.FOR
C
C*********************************************************************
  145     WRITE(*,*) 'DO YOU WANT TO PERFORM AN FFT'
          WRITE(*,*) ' YES(1) OR NO(2) '
          READ(*,*) PROMP2
          IF(PROMP2.EQ.2) GOTO 165
          DO 150 I = 1,GLEN
  150     AC(I) = VOLTS(I,1)
          OPEN(UNIT=13,FILE='FREQ.DAT')
          NB = GLEN
          N = 11
          CALL FFT(AC,N,NB)
          DO 160 I = 1,GLEN/2
          AR(I) = REAL(AC(I))
          AI(I) = AIMAG(AC(I))
          AMP(I,1) = (AR(I)**2 + AI(I)**2)**0.5
          IF(AMP(I,1) .LT. 0 ) AMP(I,1) = 0.0
          FREQ(I) = (SRATE/GLEN)*I
          WRITE(13,*) FREQ(I),AMP(I,1)
  160     CONTINUE
          WRITE(*,*) 'DO YOU WANT A PLOT OF AMP VS FREQ'
          WRITE(*,*) ' YES(1) OR NO(2) '
C          PROMP3 = 2
          READ(*,*) PROMP3
          IF (PROMP3.EQ.2) GOTO 165
          XLABL = 'FREQUENCY IN MHZ'
          YLABL = 'AMPLITUDE'
          GLEN1 = GLEN/2
          CALL PLOTS(FREQ,AMP,GLEN1,GLEN1,1,0,0,1,XLABL,YLABL,IER)
          DO 123 I=1,GLEN
          IF(AMP(I,1).LT.0) AMP(I,1) = 0
  123     CONTINUE
          WRITE(*,*) 'ENTER NMA '
          READ(*,*) NMA
          CALL SCRNQQ(3)
C*********************************************************************
C
C                          SECTION 6
C
C*********************************************************************
C
C    THIS SECTION CALCULATES THE ACOUSTO-ULTRASONIC FACTOR (AUF)
C    THE AUF VALUES ARE WRITTEN TO A FILE SWFO.DAT FOR FURTHER
C    PROCESSING.
C    VARIABLES ENCOUNTERED:
```

```
C    A1 = AUF
C
C*****************************************************************
  165   AP = 0
        AMO = 0.0
        TTOL = NGLEN/(SRATE*1000000)
C          DO 195 I = 1,GLEN
C          AMP(I,1) = TTOL*AMP(I,1)
C  195   CONTINUE
        DO 180 I = 1,GLEN/2
        AP = (AMP(I+1,1)+AMP(I,1))/2.0
        AMO = AMO + AP
  180   CONTINUE
        A1 = AMO**0.5
        WRITE(9,*) A1
        CLOSE(8)
  120   IF (.NOT.EOF(7)) GOTO 10
        STOP
        END
C*****************************************************************
C
C
C
C*****************************************************************
```

```
C***************************************************************************
C
c                        SUBROUTINE  FASTFT.FOR
c
C***************************************************************************
c
C      THIS SUBROUTINE EVALUATES THE FAST FOURIER TRANSFORM OF AN
C      COMPLEX INPUT ARRAY. THE PROGRAM IS BASED ON THE ONE IN
C      NEWLAND[22].
C      VARIABLES:
C      AC(N) = A COMPLEX ARRAY WHICH SERVES AS AN INPUT AND OUTPUT.
C      N = NUMBER OF POINTS.
C      NB = M WHEN N = 2**M.
C
C***************************************************************************
C
       SUBROUTINE FFT(A,N,NB)
       COMPLEX A(8100),U,W,T
       HI = NB
       DO 1100 J = 1,NB
 1100  A(J) = A(J)/NB
       NBD = NB/2
       NBM = NB-1
       J = 1
       DO 1200 L = 1,NBM
       IF(L.GE.J) GOTO 1300
       T = A(J)
       A(J) = A(L)
       A(L) = T
 1300  K = NBD
 1400  IF(K.GE.J) GOTO 1200
       J = J-K
       K = K/2
       GOTO 1400
 1200  J = J+K
       DO 1225 IZ = 1,18
       HI = HI/2
       IF (HI.EQ. 1) GOTO 1335
 1225  CONTINUE
 1335  NN = IZ
       PI = 3.1415926535893
       DO 1600 M = 1,NN
       U = (1.0,0.0)
       ME = 2**M
       K = ME/2
       W = CMPLX(COS(PI/K),-SIN(PI/K))
       DO 1600 J = 1,K
       DO 1700 L = J,NB,ME
       LPK = L+K
       T = A(LPK)*U
```

```
      A(LPK)=A(L)-T
1700  A(L) = A(L)+T
1600  U = U*W
      RETURN
      END
```
C
C***
C
C
C***

```
C*****************************************************************************
C
C  STATAUF.FOR: A PROGRAM TO DO STATISTICAL ANALYSIS ON THE AUF VALUES.
C
C*****************************************************************************
C
C                             SECTION 1
C
C*****************************************************************************
C
C  THIS SECTION MODIFIES THE VALUES OF AUF IF NECESSARY. THE AUF VALUES
C  STORED IN A FILE (GENERATED FROM AUFACT.FOR IS USED. THE USER SHOULD
C  KEY IN  THE NUMBER OF AUF VALUES IN THE FILE.
C
C  VARIABLES :
C    X1(I) = REAL AND IS THE OBTAINED AUF VALUE WHICH IS MODIFIED.
C    N     = NUMBER OF AUF VALUES IN THE INPUT FILE.
C
C*****************************************************************************
        IMPLICIT REAL*8(A-H,O-Z)
        REAL P,A,B,X
        INTEGER IER
        DIMENSION X1(101),Z(100)
        N=50
        DO 10 I = 1,N
        READ(2,*) X1(I)
   10   CONTINUE
        XT = 0.0
        XLT = 0.0
        XLP = 0.0
        DO 20 I = 1,N
C       X1(I) = (X1(I)-0.50)*2.0
        WRITE(3,*) X1(I)
C*****************************************************************************
C
C                             SECTION 2
C
C*****************************************************************************
C
C     THIS SECTION CALCULATES THE MEAN, VARIANCE AND THE PARAMETERS OF
C     THE BETA DISTRIBUTION ALPLA AND BETA.
C     VARIABLES:
C     XB AND SS = MEAN AND VARIANCE OF THE SAMPLE DATA.
C     A AND B = REAL AND ARE THE PARAMETERS OF THE BETA DISTRIBUTION.
C
C*****************************************************************************
        XT = XT + X1(I)
        XLT = DLOG(X1(I))+ XLT
        XLP = DLOG(1.-X1(I))+XLP
   20   CONTINUE
```

```
        XLT =-XLT/N
        XLP = -XLP/N
        XB = XT/N
        ST = 0.0
        DO 30 I = 1,N
        ST = ST + ((X1(I)-XB)**2)
  30    CONTINUE
        SS = ST/N
C       WRITE(6,*) XB,SS
        A = XB**2*(1.-XB)/SS - XB
        B = A*(1.-XB)/XB
        WRITE(4,*)   A,B,XB,SS
C******************************************************************************
C
C                           SECTION 3
C
C******************************************************************************
C
C       THIS SECTION USES THE SUBROUTINE MDBETI AND GIVES THE VALUES
C       OF AUF AT VARIOUS PERCENTAGE POINTS. (IE. TO GENERATE DATA SET
C       FOR PLOTTING CUMULATIVE DISTRIBUTION FUNCTION).
C       VARIABLES:
C       P = PERCENTAGE POINT (BETWEEN 0.0 AND 1.0 ).
C       A,B = ALPHA AND BETA CALCULATED EARLIER.
C       X = OUTPUT OBTAINED BY PASSING PARAMETERS A,B AND P TO MDBETI.
C       X IS THE AUF(STATISTICAL) VALUE.
C
C******************************************************************************
        Z1 = 1.0
        Z(1) = Z1/N
        NN = N-1
        DO 40 I= 1,NN
        Z(I+1) = Z1/N + Z(I)
  40    CONTINUE
        DO 50 I = 1,N
        P = Z(I)
        CALL MDBETI(P, A, B, X, IER)
        WRITE(6,*) I,X1(I),P,X
        WRITE(8,60) P,X
  60    FORMAT(1X,2(F7.5,3X))
  50    CONTINUE
        STOP
        END
C******************************************************************************
C
C
C******************************************************************************
```