COLLEGE OF ENGINEERING

SHORT BEAM SHEAR TESTS OF POLYMERIC LAMINATES AND UNIDIRECTIONAL COMPOSITES: FINAL REPORT
NASA GRANT NSG-1254

W. W. Stinchcomb and E. G. Henneke

Engineering Science and Mechanics Department
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

BLACKSBURG, VIRGINIA

SHORT BEAM SHEAR TESTS OF POLYMERIC LAMINATES AND UNIDIRECTIONAL COMPOSITES: FINAL REPORT
NASA GRANT NSG-1254

W. W. Stinchcomb and E. G. Henneke

Engineering Science and Mechanics Department
Virginia Polytechnic Institute & State University
Blacksburg, Virginia 24061

Submitted to

N80-25381 #

NASA LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665

June 1980

1.0 Introduction

All recent signs indicate that we are entering a revolutionary stage in the use of advanced composite materials. More and more applications are evolving in the aerospace, ground transportation and sporting industries. While a considerable amount of information has been obtained in the past one-and-a-half decades on the behavior of composite materials, much yet needs to be done, especially in the area of failure theories for design. The present, most evident characteristic of composite failure is that it does not appear to be caused by the propagation of a single, through-crack in a self-similar fashion. Hence, fracture mechanics is not directly applicable to the study of composite materials failure. The growing use of composites, together with this lack of knowledge of failure criteria, demands that more studies be performed on the mechanical behavior characteristics of these materials.

It is apparent that there will be more and more demand from designers, manufacturers, and consumers for stringent quality control and for some degree of assurance that the products designed with composite materials will serve safely for the intended lifetime. One way to ensure this, of course, is to grossly overdesign. Because of the cost of composite materials such a design philosophy might, however, be cost prohibitive and, furthermore, would not allow the designer to take full advantage of the weight savings that can be effected by using composites. Hence reliable and conclusive nondestructive testing and evaluation procedures must be developed for the examination of the integrity of composites. As noted above, composites do not fail by the propagation of a single crack. Thus NDT procedures that have been established for the detection of such flaws in homogeneous materials will not tell the complete story about composite behavior.

Recent researchers have noted in the literature a need for a change in the philosophy of NDT. D. O. Thompson [1] noted that there are problem areas in NDE which are likely to escape solution unless a scientific understanding of the problem is obtained. He noted further that, generally, the development of a scientific understanding of the causes of failure problems and their relation to the material parameters which can be used as diagnostic tools for the prediction of impending failure has not been a standard NDE development procedure. Vary [2] noted that "there is a growing consensus that the field of NDE encompasses a wider area than merely that of overt flaw detection." Recent studies were cited [2] that have indicated the possibility of using NDE methods to supplement and, in some cases, even replace destructive methods for characterizing the properties of engineering materials.

It is evident that this new philosophy must be used in performing the development of NDE methods for composites. Since single flaws apparently do not matter, NDE methods must be developed that will characterize the integrated effect of damage, i.e., the damage state, in composites and relate this to the expected load carrying ability or the expected lifetime of the material. The study of NDE in composites perhaps offers a somewhat unique opportunity for researchers. Since the study of composite failure processes is still in its infancy, NDE methods can be developed simultaneously with, and even add to, the understanding of composite failure. Philosophically, it may be better to approach the problem in this fashion than to use the former approach of waiting to learn what kind of flaw causes failure and then trying to develop techniques to locate that particular flaw.

The majority of studies that have been performed to the present time in the area of NDE in composites have concentrated on determining the ability to detect specific kinds of flaws in composites without regard to the collective role these flaws play in the ability of the material to withstand load. These studies have been important to the point that they show which NDE techniques are applicable to composites and what their advantages and limitations are. Hence they can serve as a basis for developing techniques capable of answering the more important question: What is the relation between NDE measured parameters, the damage state, and the mechanical behavior of the material?

A great deal of work in the nondestructive investigation of composite materials of a qualitative nature has appeared in the literature. However, only a relatively small number of people have addressed the problem of attempting to quantitatively relate detected defects or damage with mechanical or other physical properties of composites. The qualitative work has emphasized the need for determining the type of defects that can be detected, the best NDT techniques for detecting each type, and finally, the minimum size of defects detectable. Many different kinds of damage modes occur in composites: delamination, broken fibers, fiber-matrix disbonds, matrix porosity, fiber misalignment, etc. These damage modes may occur during loading or may be inherent in the manufacture of the material. Obviously, some NDT methods are better than others for detecting specific flaw types in specific composite material systems.

A recent report on the state-of-the-art of NDT of composite materials has detailed some of the specific findings reported in the literature [3]. As a short summary of this report the following points are noted: Radiography has been found capable of determining fiber spacing, misalignment, and fracture; the presence of inclusions; and the location of large areas of porosity. Thermal methods reveal lack of bonding, delaminations, inclusions and lack of adhesive. Ultrasonics has capabilities in the above stated areas but is especially useful for determining elastic properties, resin-rich or resin-poor regions, voids, and extensive microcracking. Ultrasonic spectroscopy can distinguish delaminations from other flaw types. C-scanning is useful for obtaining plan views and is sensitive to 1/2% void content variations. There is, however, a need for developing a more accurate method of determining void content since the shear properties of resin matrix composites are very sensitive to this content. Due to conflicting statements in the literature regarding the capability of using velocity or attenuation methods for determining void content, this area, in particular, should be studied systematically. Acoustic emission has been demonstrated to have great potential, but there is a need for more care in defining the measurement system parameters so quantitative comparisons of experimental studies can be made. A number of reports present interesting and potentially promising techniques for investigating various facets of composite material behavior. However for the most part, the results presented are only preliminary. There seems to be very little follow through with in-depth studies, perhaps because of the lack of funding. Systematic studies are desperately needed in nearly every area discussed in the cited report.

While a great deal of work has been performed in qualifying which NDT methods are optimum for detecting specific types of flaws, little work has been done to determine the effect of the detected flaws on mechanical properties such as stiffness, strength, fatigue lifetime, or residual strength. The degree to which the defects that can be found are responsible for ultimate failure is not clear at this time; nor is it clear how the defects are responsible for failure observed below predicted values. In some instances, a flaw in a composite can be detrimental in quasi-static loading. But if low maximum cyclic loads are applied first, the effect of the flaw is completely eliminated as far as the load carrying capacity of the composite is concerned. A major effort is required to perform quantitative nondestructive evaluation of composite materials concurrently with a program characterizing their mechanical properties. Such a program would have the major advantages of establishing a data base, developing models that relate the measured NDT parameters to the parameters controlling the mechanical properties of the composite, and quantifying the damage processes responsible for failure in composites.

2.0 Technical Overview

2.1 Past Work Performed

The need for high strength, light weight materials to meet the design specifications for service in high temperature environments has attracted much attention to graphite-polyimide composites. As various candidate materials were considered, suitable screening tests were employed to monitor fabrication variables and evaluate material properties. One of these tests, the short beam shear test (ASTM Standard D2344), is frequently used as a screening test because of the ease and simplicity of testing large numbers of small, economically sized, specimens.

In the present investigation, the short beam shear test was used to evaluate unidirectional P13N graphite polyimide laminates fabricated under different molding pressures [4]. During the analysis of the test results, failure modes other than shear were observed in the short beam shear specimens. It was not uncommon to have several failure modes, such as bending, microbuckling (local failure at the point of load application), or shear occur in specimens of the same material and identical curing treatments. The variety of responses and failure modes makes it impossible to interpret and compare the test data since the short beam shear analysis is based on a shear mode of failure.

Other limitations of the short beam shear test were also noted. The short beam shear test is a destructive test and does not provide information about the initial quality of the material that can be compared with response data. It appears as if the shear failure mode occurs only in those specimens which are of poor initial quality as revealed by nondestructive tests such as ultrasonic C-scans. Specimens having less severe imperfections fail in other modes, such as microbuckling or a combination of shear and microbuckling. Thus, the results of the mechanical tests are very sensitive to the quality of the material and that quality needs to be evaluated in order to understand the response of the composite.

Alternative procedures for nondestructive evaluation of graphite polyimide composites have been proposed, adapted, and used in this investigation to provide correlation between material quality and material response. These include ultrasonic C-scan, ultrasonic pulse echo, stiffness, and a technique known as the stress wave factor (SWF). Each of these is discussed in the following paragraphs with reference to their application to the present work.

Two of the more common nondestructive investigation methods are ultrasonic C-scan and ultrasonic pulse-echo. These methods have been used to detect some types of fabrication related and mechanical load induced damage in composite laminates. In particular, the C-scan is frequently used to obtain a qualitative plan view of regions of a laminate which are inferior in their ability to transmit ultrasonic energy due to defects, scattering centers, or other localized material imperfections. In the present study, short beam shear specimens taken from these indicated regions failed in an interlaminar shear mode at low loads compared to specimens taken from "good" regions of the same laminate [4]. The C-scan is particularly suited for detecting defects in the plane of a composite panel and mapping regions of relatively good and bad quality in the panel. However, it is not possible to quantify the severity of a defective region on an absolute scale and the data is most accurately interpreted when it is compared to a C-scan of a calibrated test standard.

The ultrasonic pulse-echo method can be used to measure the attenuation of ultrasonic pulses which have traveled through a composite laminate. This method has the advantage of providing a quantitative measure of damage which can be correlated with mechanical properties such as stiffness or strength [5]. Although interlaminar defects such as delamination or defective ply interfaces will attenuate ultrasonic waves, recent studies have shown that interior cracks act as diffraction gratings to produce a change in the apparent attenuation [6]. In these studies, very distinct changes in ultrasonic attenuation corresponded to the initiation of cracks in the 90° plies of quasi-isotropic graphite epoxy specimens. Another advantage of the pulse-echo method is that it serves as a real time monitor of damage growth during static and cyclic mechanical loading. As damage develops in off-axis plies, the ultrasonic attenuation changes in a manner dependent upon the number of cracks in the field of the transducer, the spacing of the cracks, and the crack opening.

In order to apply the pulse-echo method to composite specimens which are of intermediate thickness (the order of 16 plies), it was necessary to modify the buffer rod method discussed in references [7] and [8]. The method developed as part of this investigation [5] is applicable to any specimen of intermediate thickness that can be modeled by a homogeneous material in the frequency range used. Furthermore, this method can be used on a composite material that has only one accessible surface and offers several advantages over alternative methods discussed in references [7] and [8]. Firstly, for specimens having very high attenuation, it requires only one returning echo from the specimen and two echoes from the buffer block to determine the attenuation of the specimen. Secondly, the technique allows for an absolute value of attenuation to be calculated for the specimen, within the limitations established by the assumptions used in the model. Thirdly, the technique allows for judicious choice of which returning echoes are to be used for amplitude measurements. This is in contrast to Papadakis' technique [8] which requires two adjacent returning echoes from the specimen for the attenuation measurement. Thus with the present technique, one can choose those echoes with largest amplitudes so that minimum experimental error is involved in the measurement.

For P13N graphite-polyimide composite specimens, the modified ultrasonic buffer block method developed in this investigation yields a quantitative parameter (the initial attenuation) measured by a nondestructive testing technique that correlates well with the failure strength measured by the short beam shear test method. The data obtained by this technique are also shown to correlate well with the qualitative assessment of the quality of the material as determined by ultrasonic C-scan studies. Generally, those specimens having higher values of attenuation were found to fail at lower values of applied load. If a panel of material is generally of overall good quality, there is a poor correlation between attenuation values and failure loads of the short beam shear specimens cut from that panel. This result is likely to be expected since the better quality material will have a smaller standard deviation of both failure loads and attenuation, and hence the spread in both attenuation and failure load values will be more sensitive to experimental and random errors. However, for material that has a wider variation in quality, it has been found that a good correlation exists between the attenuation and failure strengths.

Stiffness is a material property which can be easily and nondestructively determined to monitor the response of a material under load. Unlike strength, stiffness decreases monotonically with damage and can be used as an indicator of the damage state. In some situations, initial values of stiffness may be incorporated in an accept/reject criterion for a structural part, or changes in stiffness during service may be incorporated in a failure criterion. Stiffness data correlates very well with data from other techniques which measure damage in composite laminates. Specifically, a sharp change in ultrasonic attenuation and acoustic emission count rate occur simultaneously with a knee or step in the stress-strain response [9]. Good correlation between stiffness change and delamination have also been reported [10]. For the particular case of graphite-polyimide short beam shear specimens, the slopes of the load-deflection curves provided a measure of the stiffness of each specimen. Although the data show some scatter, there is a positive correlation between the initial stiffness and failure load. Those specimens with low values of initial stiffness generally had low values of failure load in the short beam shear test.

2.2 Work performed during past year

2.2.1 Test methods

A series of nondestructive tests were conducted on unidirectional graphite polyimide specimens to evaluate the sensitivity of several NDE methods to detecting defects in the same set of specimens. Graphite polyimide panels were C-scanned at four trigger levels to locate "good" and "bad" regions in the panel. At the present, "good" regions are defined as those which do not attenuate the ultrasonic waves as much as "bad" regions do. Four specimens 10" x 1" were machined from each region. Specimens 3, 4, 6 and 7 were taken from "good" regions, and specimens 1, 2, 5, 8 were taken from "bad" regions. Following the ultrasonic C-scan, four types of nondestructive tests were run on each specimen: (1) point-to-point ultrasonic attenuation measurements, (2) continuous ultrasonic attenuation measurements, (3) stress wave factor measurements, and (4) stiffness measurements.

Point-to-point attenuation measurements were made at one-half inch intervals along the center six inches of each specimen using the technique described in reference [5]. Continuous attenuation measurements were made using a Matec attenuation recorder together with the C-scan apparatus. The data provided a continuous record of attenuation across the width of each specimen rather than only an indication of where the attenuation exceeded a preset trigger level. The across-the-width scans were made in 0.1 inch intervals along the center portion of the specimens.

The stress wave factor measurements using the technique developed by Vary, et al., [11-13] were also taken at one-half inch intervals along the center six inches of each specimen. The stress wave factor method is an NDT technique utilizing two basic ultrasonic methods, acoustic emission and pulse-echo. In this technique, shown schematically in Fig. 1, a high frequency ultrasonic pulse (5 MHz) is generated in the specimen in a fashion identical to that of the standard pulse-echo method. An acoustic emission transducer is mounted a fixed distance away from the ultrasonic transducer on the same side of the specimen. "Leakage" waves established by the ultrasonic transducer by diffraction, reflection, or surface phenomena are detected by the low-frequency AE transducer (100 KHz) and counted by a standard AE counting apparatus. The parameter obtained, called the stress wave factor, SWF, by Vary, is simply the measured count rate. Vary's technique is based upon the thesis that the easier it is for a stress wave to propagate in a material, the higher the value of the SWF. High values of the SWF imply better stiffness and strength properties of the material. Vary has also correlated the SWF with micro-void content and fracture site [2].

An SWF test rig was constructed at Virginia Tech based upon the reports and papers of Vary [11-13]. A number of difficulties have been encountered during our attempt to reproduce Vary's method and to interpret the resulting data. A major point to be considered in making an SWF measurement was found to be the fact that the AE counter must be synchronized with the ultrasonic pulsing unit. Specifically, the gate on the counter must open with an initial pulse and close after a fixed number of pulses has occurred. It is not necessary that the number of pulses be known, but the number of pulses must be identical for each measurement. If this detail is not observed, the SWF measurement varies

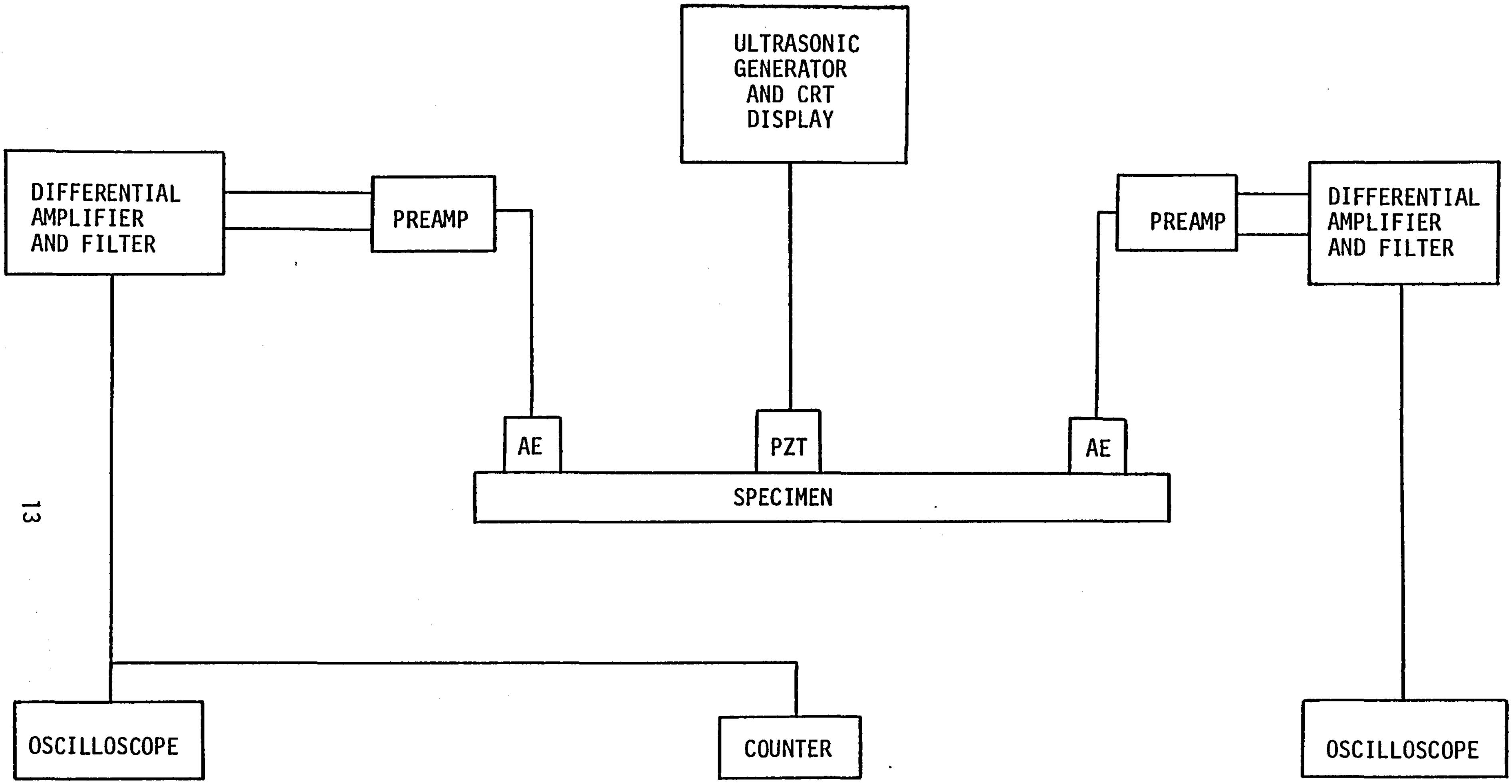


Fig. 1. Schematic diagram of experimental set-up to measure stress wave factor.

considerably from measurement to measurement. The particular counter available in our laboratory, while having the advantage of a very stable and accurately adjustable trigger level, can not be synchronized with an external apparatus. Even when an attempt was made to overcome this problem by setting a long gate time (1 sec) and a high pulse repetition rate (500 Hz), the variation from measurement to measurement was 100 or more counts (20 percent or more of the total counts). In order to utilize our equipment, it was found necessary to trigger the ultrasonic pulser manually (usually ten times) and to average the SWF by obtaining the resulting value for each of these ten pulses. By this technique, it was finally possible to obtain more reproducible values of SWF (within one count over a repeated number of measurements). Of course, when the transducers are removed and recoupled to the specimen, the value of SWF will change. Results are given in Tables 1a-d where the scatter from average SWF are those values obtained by removing the transducers, cleaning the surface, and recoupling the transducers for additional measurements.

A second difficulty with this technique, as with all ultrasonic methods which do not utilize a submergence of the specimen and transducer into a coupling medium such as water, is the inherent problem of obtaining consistent coupling of transducer and specimen. Utmost care must be taken to obtain as consistent a bond as possible so that the effect of varying amounts of energy coupled into the specimen is minimized. A jig was constructed to hold the pulsing transducer and AE transducer a fixed distance apart and to allow a weight to be placed atop the jig to maintain a constant pressure between the transducers and the specimen. After sufficient training and practice by the operator it

Table 1a. ULTRASONIC ATTENUATION AND STRESS WAVE FACTOR DATA

Specimen: 3

Location	Average Attenuation (dB)	Scatter from Average Attenuation (dB)	Average SWF	Scatter from Average SWF
1	14.0	+1.3/-2.0	472	+28/-22
2	13.3	+1.9/-1.0	553	+7/-4
3	13.9	+0.6/-1.1	569	+11/-15
4	13.7	+1.0/-0.7	568	+22/-38
5	12.8	+0.9/-0.6	545	+24/-15
6	11.5	+1.4/-0.8	571	+9/-15
7	11.4	+0.7/-0.5	534	+36/-23
8	12.5	+2.0/-1.2	690	+38/-36
9	15.5	+2.9/-1.8	609	+12/-23
10	19.2	---	581	+29/-38
11	17.4	+1.8/-1.8	495	+29/-25
12	13.4	+1.8/-1.1	494	+7/-8

Table 1b. ULTRASONIC ATTENUATION AND STRESS WAVE FACTOR DATA

Specimen: 4

Location	Average Attenuation (dB)	Scatter from Average Attenuation (dB)	Average SWF	Scatter from Average SWF
1	No reading	---	299	+60/-49
2	No reading	---	489	+3/-4
3	13.5	+0.0/-0.0	477	+43/-25
4	13.1	+0.2/-0.2	513	+34/-20
5	13.0	+0.3/-0.2	572	+17/-13
6	13.2	+0.5/-0.4	510	+27/-15
7	13.4	+0.2/-0.2	497	+24/-37
8	11.5	+0.1/-0.2	554	+16/-24
9	11.6	+0.1/-0.1	504	+25/-23
10	12.0	+0.6/-0.4	530	+30/-37
11	12.5	+0.0/-0.0	525	+25/-19
12	13.9	+0.4/-0.6	390	+16/-8

Table 1c. ULTRASONIC ATTENUATION AND STRESS WAVE FACTOR DATA

Specimen: 6

Location	Average Attenuation (dB)	Scatter from Average Attenuation (dB)	Average SWF	Scatter from Average SWF
1	17.0	+0.4/-0.3	376	+6/-5
2	11.8	+0.3/-0.2	520	+35/-25
3	11.8	+0.1/-0.1	462	+4/-3
4	13.5	+0.1/-0.1	509	+16/-12
5	10.8	+0.1/-0.1	535	+27/-25
6	11.1	+0.1/-0.2	442	+14/-12
7	11.6	+0.6/-0.3	494	+25/-34
8	12.8	+0.1/-0.1	559	+24/-13
9	10.2	+0.0/-0.0	556	+36/-22
10	10.1	+0.5/-0.4	504	+36/-43
11	13.0	+0.8/-0.6	514	+8/-14
12	13.4	+1.0/-0.6	457	+65/-61

Table 1d. ULTRASONIC ATTENUATION AND STRESS WAVE FACTOR DATA

Specimen: 7

Location	Average Attenuation (dB)	Scatter from Average Attenuation (dB)	Average SWF	Scatter from Average SWF
1	12.4	+0.7/-0.4	413	+10/-16
2	14.6	+0.2/-0.4	554	+23/-20
3	13.2	+0.1/-0.1	523	+5/-3
4	12.5	+0.9/-0.9	546	+2/-3
5	12.2	+0.5/-0.7	552	+7/-5
6	10.4	+0.2/-0.4	505	+11/-10
7	15.4	+4.1/-2.3	575	+10/-5
8	17.7	+0.6/-0.8	582	+6/-7
9	18.3	+0.2/-0.3	604	+3/-3
10	19.5	---	543	+27/-19
11	14.1	+0.3/-0.3	462	+8/-10
12	13.4	+0.2/-0.1	344	+16/-22

was possible to obtain acceptable, reproducible values of SWF on the same portion of the specimen after complete removal of the test jig, clean-up of the specimen, and reapplication of the coupling agent and transducers (within approximately 5 percent).

Stiffness values were computed from load and strain data recorded during three point bending and tension mechanical tests to a low "non-destructive" load level. Axial and transverse strains were measured with 0.125 inch gage length, 0°-90° strain gages located 1.5 inches from the center of the specimen. This position corresponded to the "quarter-point" in the three point bending tests. A one inch gage length extensometer located in the center of the specimen was also used during the tension tests.

Values of bending stiffness and fiber direction modulus (E_{11}) were computed from the slopes of the bending moment vs. fiber direction strain and axial load vs. fiber direction strain curves for flexural and axial loading, respectively. Values of Poisson's ratio were determined from the slopes of the transverse strain vs. axial strain curves. The data are presented in Table 2.

2.2.2 Results

SWF and attenuation values for specimens 3, 4, 6 and 7 are given in Table 1(a-d). The initial C-scans of the graphite polyimide panels indicated that these specimens were cut from "good" regions. It was not possible to send an ultrasonic pulse through specimens 1, 2, 5 and 8 from the "bad" regions; therefore, no attenuation measurements could be made for these specimens. It was thought that the SWF and/or the point-to-point attenuation might provide a quantitative measure of the

Table 2. MEASURED VALUES OF ELASTIC MODULI

Specimen	Test Method: Flexure		Test Method: Tension		
	E_B (in.-kips)	ν_B	E_{11SG} (Msi)	E_{11EXT} (Msi)	ν_T
1	---	---	---	17.4	---
2	17.3	0.31	14.3		0.31
3	---	---	---	18.2	---
4	29.1	0.31	16.2		0.26
5	25.5	0.33	16.7		0.31
6	---	---	---	18.4	---
7	23.2	0.29	18.2		0.30
8a	20.5	0.28	16.9	17.5	0.32
8b	20.1	0.32	17.5		0.31

E_B - bending stiffness

ν_B - bending Poisson's ratio

E_{11SG} - Young's Modulus in fiber direction from strain gage data

E_{11EXT} - Young's Modulus in fiber direction from extensometer data

ν_T - tension Poisson's ratio

quality of the material rather than a "good" or "bad" indication relative to a trigger level on the C-scan apparatus. However, as can be seen by examination of Table 1, there is little or no consistent correlation between the SWF and the attenuation parameters. It was thought that low attenuation values should correlate with high SWF values, and vice-versa, if both techniques are indeed measuring the same specimen characteristics.

The reason for the failure of good correlation between SWF and attenuation is presently not clear. There are several reasons why the present results may be inconsistent. Firstly, the "good" specimens for which attenuation measurements could be made were of nearly uniform quality. The "bad" specimens, of course, were so uniformly bad that no attenuation measurements at all could be made. Hence, the inconsistency may be due to normal data scatter. To obtain better correlation one might have to investigate a more continuous range of material quality. Secondly, it is possible that the SWF technique and ultrasonic attenuation method are measuring different specimen characteristics. While this does not appear likely, insufficient information on the SWF method is presently available to be able to firmly judge the phenomena being measured by this technique. Just a few of the questions which must be answered are: How are the "leakage" waves established in the specimen?, What modes are set up?, What specimen characteristics filter the high frequency waves into the low frequency waves that are monitored by the AE transducer? Thirdly, even with great operator care, both techniques are so sensitive to the operator's skill that experimental measurements may be questionable. Obviously, additional work would be required before the answers to this difficulty could be obtained. As with many

NDT methods, however, both of these techniques do appear to offer sufficient potential for use in composites that additional work is merited.

Table 3a-d compares values of point-to-point ultrasonic attenuation (α) and stress wave factor (SWF) with the continuous attenuation recorded at increments along the length of specimens 3, 4, 6 and 7. Again, the apparent agreement between the data is poor in that α and SWF values increase and decrease over the length of the specimen and the values of continuous attenuation generally increase along the length. The continuous attenuation data, however, do compare favorably with conventional C-scan results in that both indicate some change in the quality of the material along the length of the specimen. Although the point-to-point technique and the continuous scan technique both measure the attenuation of ultrasonic signals, the point-to-point method does require breaking and forming the transducer to specimen couple each time a measurement is made as discussed previously. The continuous scan method, however, utilizes a continuous and consistent coupling between the specimen and transducer in the form of a column of water, thereby eliminating an important source of error in the data.

Some general trends in the elastic moduli data can be observed although it is not possible to attach significance to the actual values because of the limited data. The observations are based on the data for "good" specimens (numbers 3, 4, 6, and 7) and "bad" specimens (numbers 1, 2, 5, and 8) shown in Table 2. Two strain gages were attached to specimen 8 at positions a and b equidistant from the loading point.

- The highest value of bending stiffness (29.1 in.-kips) was obtained from a good specimen (no. 4), and the lowest value (17.3 in.-kips)

Table 3a. POINT-TO-POINT ATTENUATION, STRESS WAVE FACTOR, AND CONTINUOUS ATTENUATION DATA.

Specimen: 3

Location	α	SWF
11	17.4	495
10	19.2	581
9	15.5	609
8	12.5	690
7	11.4	534
6	11.5	571
5	12.8	545
4	13.7	568
3	13.9	569
2	13.3	553

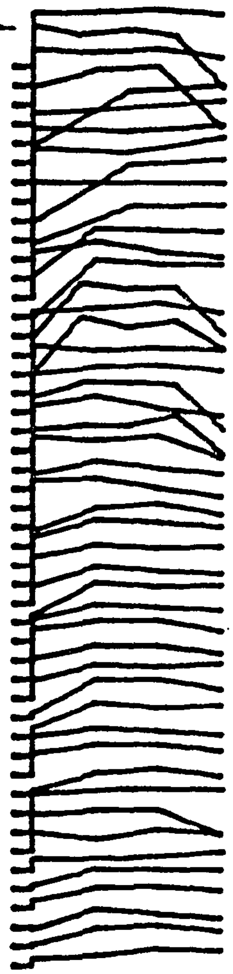


Table 3b. POINT-TO-POINT ATTENUATION, STRESS WAVE FACTOR, AND CONTINUOUS ATTENUATION DATA.

Specimen: 4

Location	α	SWF
11	12.5	525
10	12.0	530
9	11.6	504
8	11.5	554
7	13.4	497
6	13.2	510
5	13.0	572
4	13.1	513
3	13.5	477
2	----	489

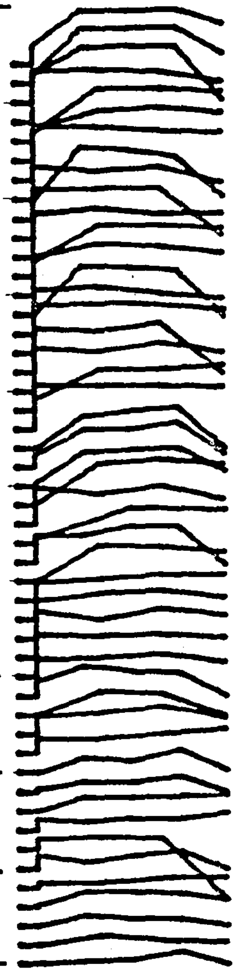


Table 3c. POINT-TO-POINT ATTENUATION, STRESS WAVE FACTOR, AND CONTINUOUS ATTENUATION DATA.

Specimen: 6

Location	α	SWF
11	13.0	514
10	10.1	504
9	10.2	556
8	12.8	559
7	11.6	494
6	11.1	442
5	10.8	535
4	13.5	509
3	11.8	462
2	11.8	520

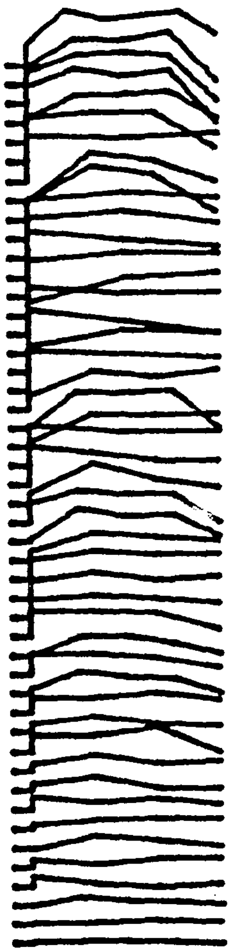
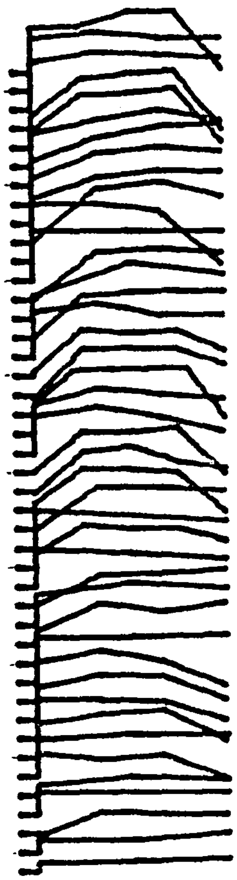


Table 3d. POINT-TO-POINT ATTENUATION, STRESS WAVE FACTOR, AND CONTINUOUS ATTENUATION DATA.

Specimen: 7

Location	α	SWF
11	14.1	462
10	19.5	543
9	18.3	604
8	17.7	582
7	15.4	575
6	10.4	505
5	12.2	552
4	12.5	546
3	13.2	523
2	14.6	554



was obtained from a bad specimen (no. 2).

- The average of the bending stiffnesses for specimens 4 and 7 is greater than the average of the bending stiffnesses for specimens 2, 5, and 8.
- The highest value of Young's Modulus from strain gage data (18.2 Msi) was obtained from a good specimen (no. 7) and the lowest value (14.3 Msi) was obtained from a bad specimen (no. 2).
- The average Young's Modulus from strain gage data for specimens 4 and 7 is greater than the average Young's Modulus from strain gage data for specimens 2, 5, and 8.
- The highest value of Young's Modulus from extensometer data (18.4 Msi) was obtained from a good specimen (no. 6) and the lowest value (17.4 Msi) was obtained from a bad specimen (no. 1).
- The average Young's Modulus from extensometer data for specimens 4 and 7 is greater than the average Young's Modulus from extensometer data for specimens 2, 5, and 8.
- Although the differences in values of Poisson's ratio are small, the average values of Poisson's ratio in bending and axial tension of "bad" specimens are slightly greater than the corresponding values of "good" specimens.

Figure 2 shows curves of bending moment vs. flexural strain for two "good" and two "bad" specimens. Specimen 2 had the lowest values of bending stiffness and tensile Young's Modulus of all specimens tested.

Although some correlations of a general nature can be made between stiffness related response and ultrasonic C-scan data, specific relationships cannot be made at this point. For example, C-scans of specimens

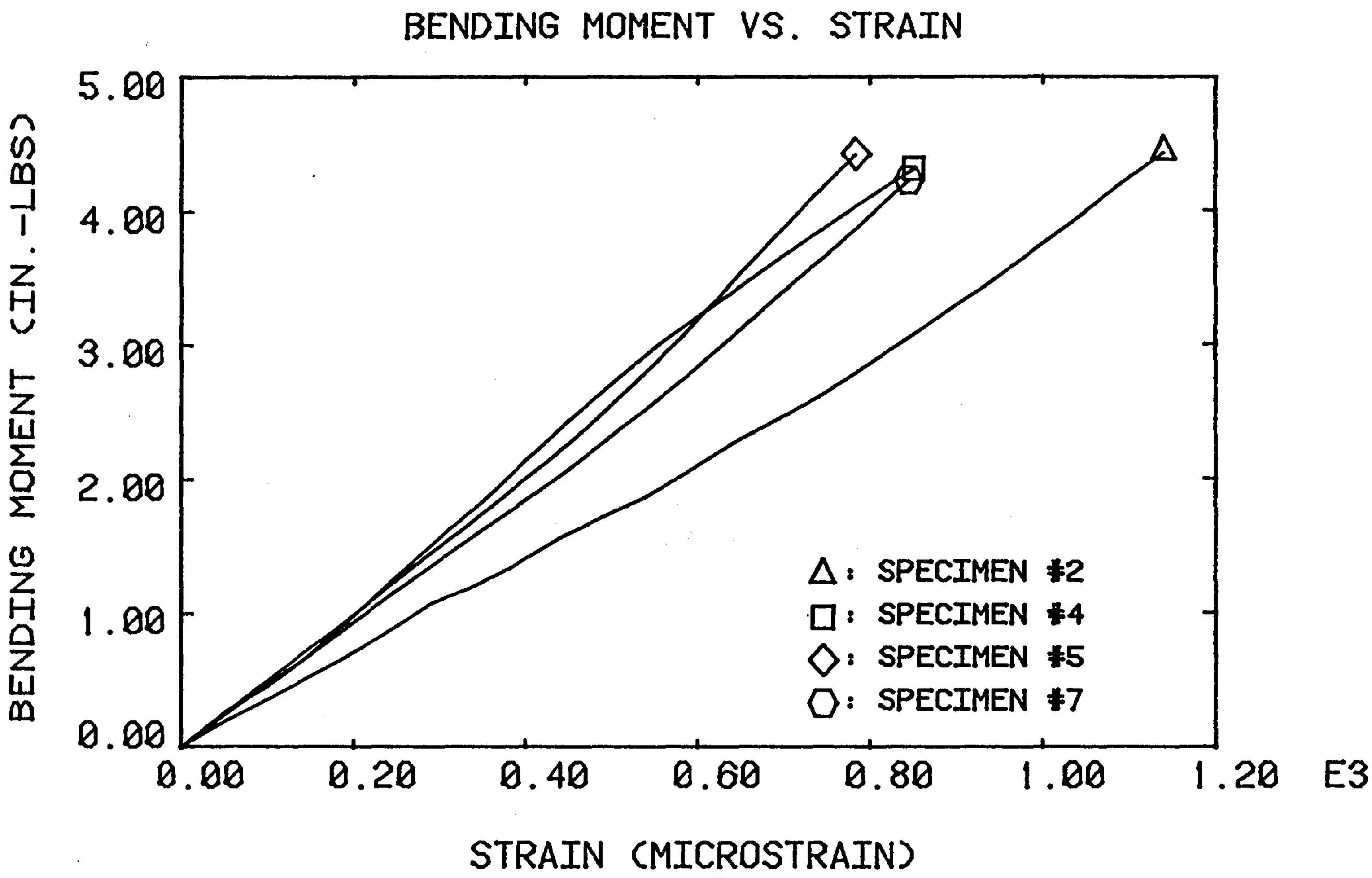


Fig. 2. Bending moment vs. strain curves for graphite polyimide specimens.

2 and 5 were very similar and quite different from C-scans of specimens 4 and 7. However, only the response of specimen 2 was noticeably different from that of the other three specimens.

2.2.3 Summary

The following statements are presented concerning the nondestructive techniques used in this investigation and the results obtained from these techniques.

1. A general agreement was observed between the data from ultrasonic C-scans and continuous ultrasonic attenuation scans. However, the agreement was only in identifying regions of relative "good" and "bad" quality.
2. An ultrasonic scanning technique with continuous output is more desirable than a scanning technique which provides an on-off output relative to a preset trigger level. Continuous output could be in the form of a voltage proportional to the amplitude of a selected echo or a continuous gray scale based on the amplitude of the echo.
3. It was not possible to interpret the point-to-point attenuation data and the stress wave factor data. A serious limitation of any technique which requires that a transducer contact a test article and be moved on the article is the variable quality of the couplant at the transducer/specimen interface.
4. A general correlation between C-scan data and mechanical properties could be made in that some values of stiffness could be "explained" by looking at the C-scans. However, it was not possible to predict the relative stiffnesses from C-scan records, or any other nondestructive data.

5. There is a growing need for establishing relationships (both qualitative and quantitative) between defects in composite materials and the material response. The general approach to satisfying this need should be based on systematic and thorough investigations to:

   i) develop a more complete understanding of the mechanics of the response of composite materials

   ii) develop an understanding of the nondestructive techniques as they interact with composite materials

   iii) develop these techniques to the state that the information they provide can be related to the response process so that some predictive capability can be attained.

References

1. Thompson, D. O., "Advanced NDE Techniques", Prevention of Structural Failure, No. 5, 1975, pp. 114-145.

2. Vary, A., "Quantitative Ultrasonic Evaluation of Mechanical Properties of Engineering Materials", N.B.S. Internat. Symp. on Ultrasonic Materials Characterization, June 7-9, 1978.

3. Henneke, E. G. and Duke, J. C., Jr., "A Review of the State-of-the-Art of Nondestructive Evaluation of Advanced Composite Materials", Union Carbide Corp., Oak Ridge National Laboratory, Sept., 1979.

4. Stinchcomb, W. W., Henneke, E. G., Price, H. L., "Use of the Short Beam Shear Test for Quality Control of Graphite-Polyimide Laminates", Reproducibility and Accuracy of Mechanical Tests, ASTM STP 626, American Society for Testing and Materials, 1977, pp. 96-109.

5. Hayford, D. T., Henneke, E. G., and Stinchcomb, W. W., "The Correlation of Ultrasonic Attenuation and Shear Strength in Graphite-Polyimide Composites," J. Composite Materials 11, October, 1977.

6. Hayford, D. T. and Henneke, E. G., "A Model for Correlating Damage and Ultrasonic Attenuation in Composites", Composite Materials: Testing and Design (Fifth Conference), ASTM STP 674, S. W. Tsai, Ed., American Society for Testing and Materials, 1979, pp. 184-200.

7. McSkimin, H. J., "Ultrasonic Measurement Techniques Applicable to Small Solid Specimens", J. Acous. Soc. Amer. 22, (1950), p. 413.

8. Papadakis, E. P., "Ultrasonic Attenuation in Thin Specimens Driven through Buffer Rods," J. Acous. Soc. Amer. 44, (1968), p. 724.

9. Stinchcomb, W. W., Reifsnider, K. L., Yeung, P., and Gibbins, M. N., "Investigation and Characterization of Constraint Effects on Flaw Growth During Fatigue Loading of Composite Materials", Final Report: NASA Grant NSG-1364, June, 1979.

10. O'Brien, T. K., "Stiffness Change as a Nondestructive Damage Measurement", Mechanics of Nondestructive Testing, W. W. Stinchcomb, Editor, Plenum, 1980.

11. Vary, A. and Bowles, K. J., "Ultrasonic Evaluation of the Strength of Unidirectional Graphite-Polyimide Composites", NASA Technical Memorandum, NASA TM X-73646, April, 1977.

12. Vary, A. and Bowles, K. J., "Use of an Ultrasonic-Acoustic Technique for Nondestructive Evaluation of Fiber Composite Strength", NASA Technical Memorandum, NASA TM-73813, Feb., 1978.

13. Vary, A. and Lark, R. F., "Correlation of Fiber Composite Tensile Strength with the Ultrasonic Stress Wave Factor", NASA Technical Memorandum, NASA TM-78846, April, 1978.

End of Document