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Determination of Elastic Moduli of Fiber-Resin Composites Using an Impulse Excitation Technique

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ABSTRACT

The elastic moduli of graphite/epoxy and graphite/cyanate ester composite specimens with various laminate lay-ups was determined using an impulse excitation/acoustic resonance technique and compared to those determined using traditional strain gauge and extensometer techniques. The stiffness results were also compared to those predicted from laminate theory using uniaxial properties. The specimen stiffnesses interrogated ranged from 12 to 30 Msi. The impulse excitation technique was found to be a relatively quick and accurate method for determining elastic moduli with minimal specimen preparation and no requirement for mechanical loading frames. The results of this investigation showed good correlation between the elastic modulus determined using the impulse excitation technique, strain gauge and extensometer techniques, and modulus predicted from laminate theory. The flexural stiffness determined using the impulse excitation was in good agreement with that predicted from laminate theory. The impulse excitation/acoustic resonance interrogation technique has potential as a quality control test.

INTRODUCTION

The objective of this test program was to determine if an acoustic resonance technique could accurately measure the elastic moduli of graphite epoxy materials and thus be used to supplement data obtained by traditional mechanical test techniques. The advantage of the acoustic resonance technique explored for this memorandum is the reduced cost and time required to determine laminate stiffness.

The determination of elastic properties in composite materials typically involves the use of strain-gauged specimens subjected to mechanical loading. All aspects of both specimen preparation and testing of these specimens are costly, time consuming, and are performed on specimens prepared independently from the actual service components. The traditional elastic modulus measurements begin with the preparation of a sheet of material nominally 9 to 12 inches square. The sheet is trimmed and has fiberglass tabbing material bonded to the specimen in four places (top and bottom, front and back); the bonding of the tabs typically requires two bonding operations. The cost is further increased by the use of tapered tabs. After the tabs are applied the tensile specimens are sliced from the sheet. Prior to testing, strain gauges are applied to the specimen surface, and the lead wires are soldered to the strain gauge. The tensile specimen is loaded into a testing machine and the load versus strain is recorded. After testing, the data is reduced to provide a modulus which is taken over a strain range that varies among testing specifications[1-4].

This description of the overall procedure used to generate modulus data is provided to illustrate both the time and the expense involved in measuring the mechanical properties of composite materials. The transformation of composite materials into tensile specimens typically costs $100 per specimen and takes a week or more to accomplish. By comparison, the impulse excitation/acoustic resonance technique can be used on specimens that require substantially less preparation. The specimen used for the acoustic resonance technique need be only rectangular and of an appropriate size to have a frequency detectable by the acoustic detector. Both in-plane and flexural modes can be interrogated to provide contrasting information to confirm the laminate ply orientations. The small specimen size makes this technique potentially attractive as a quality control test via the use of tag end specimens.

BACKGROUND

Traditional techniques used to measure moduli (E) begin with its definition in terms of the applied stress (σ) and strain (ε):

$$\sigma = E\varepsilon \qquad (1)$$

and would then compute the applied stress as the applied load divided by the cross-sectional area and determine the strain from a resistance-type strain gauge or an extensometer.

The cross-sectional area of a beam with a rectangular cross section is always defined as its thickness times its width. However, the composites industry often uses the convention of "nominal ply thickness," which is the predicted thickness per ply for a given prepreg system, in place of the actual ply thickness. This dimension is largely dependent on the type of fiber used and if the prepreg is woven or uniaxial. As the actual ply thickness can deviate from the nominal ply thickness, ambiguity in the value used can lead to considerable confusion and differing moduli values. Design engineers typically will use the nominal values, because they have no knowledge of the actual ply thickness, while the materials testing personnel will provide mechanical properties calculated using the actual specimen's geometry. Since this memorandum is being written by personnel primarily involved in the testing of composite materials, all properties will be calculated using actual specimen thicknesses.

The calculation of the predicted composite stiffness was performed via classical composite laminate theory using available stiffness values for [0]° laminates. These values are either the prepreg manufacturer's data, provided at the time of purchase, or the values obtained using strain gauged [0°] laminates. The flexural stiffness matrix [D] of the laminate is defined as [5, 6]:

$$[D] = 1/3\sum_{i=1}^{m}[Q']^{(i)}[(z^{(i)})^3 - (z^{(i-1)})^3] \qquad (2)$$

where $[Q']^{(i)}$ is the off-axis-ply-stiffness-matrix of the ith ply group oriented at angle θ from the laminate axis, and $z^{(i)}$ is the distance from the neutral axis to the ith ply interface.

The longitudinal (in-plane) stiffness matrix [A] of the laminate is defined in a similar manner as [5, 6]:

$$[A] = \sum_{i=1}^{m}[Q']^{(i)}[z^{(i)} - z^{(i-1)}] \qquad (3)$$

The theoretical laminate stiffness values for this report were calculated using a software program known as Genlam [5]. The input to this software was the manufacturer's stiffness values for 0° Tension (Ex), 90° Tension (Ey), V-notch shear (Es), Poisson's ratio (ν), ply thickness and the orientations of the laminate stacking sequence.

The specimens used in this study were rectangular in shape. The flexural stiffness (E_f) of a rectangular bar in terms of the first-mode-resonance-frequency (f_f) of a beam is given as [7]:

$$E_f = 0.9465\left(\frac{m\, f_f^{\,2}}{b}\right)\left(\frac{L^3}{t^3}\right) T_1 \tag{4}$$

where m = mass, b = width, L = length, t = thickness, and T_l is a correction factor for $L/t \geq 20$ defined as:

$$T_l = [1.00 + 6.585\,(t\,/\,L)^2] \tag{5}$$

The longitudinal or in-plane (E_l) modulus is given as [8]:

$$E_l = D f_f^{\,2} L^2 \rho \tag{6}$$

where f_f = fundamental longitudinal resonance frequency in hertz, L = length, ρ = density, and D is a constant equal to 4.00 for rods and bars.

The stiffness calculations were made using software provided by the manufacturer of the acoustic resonance monitor (EMOD, ver 9.12). The software incorporates Equations 4 and 6.

EXPERIMENTAL PROCEDURE

The graphite fiber reinforced resin test specimens used for this study were obtained from various in-house projects. The specimens designated as ATM were generated during a research program aimed at developing alternate test methods for composite materials. The specimens designated as FUSE were removed from tag ends of square tubes originally intended for use in the truss structure of the Far Ultraviolet Spectrometry Explorer spacecraft. The specimens designated as SP207 were taken from panels manufactured for a SPARTAN grapple mount. The materials that were investigated with their various laminate lay-ups are presented in Table 2. The 1999 and 954-2A matrix materials are cyanate ester resins. The 1962 and 934 matrix materials are epoxies. All laminates were symmetric, 16 plies thick and approximately 1 inch wide. The length of the specimens varied from 5 to 9 inches. The exact specimen dimensions are in Table 3.

All specimens were first interrogated using impulse excitation, both in flexure and along the longitudinal axis. This measurement was performed using an off-the-shelf device (Grindo-Sonic, J.W. Lemmens, Inc., St. Louis, MO) that measures the fundamental acoustic resonance frequency of an excited specimen. The stiffness of each specimen was determined using the vibrational data for both the longitudinal and flexural modes. The components of the acoustic resonance device are shown in Figure 1. The typically used, hand-held piezoelectric probe was replaced with a microphone. It was found that the contact force required to couple the specimen to the hand-held probe either damped the specimen or caused it to move. The microphone was found to give more repeatable results than the hand held probe.

The actual excitation of the specimen was performed using a small hammer constructed from a 1/8" diameter steel ball bonded to a small nylon tie wrap. This hammer was provided by the manufacturer and has proven superior to any other means of excitation. The amount of force required to excite a specimen has not been quantified, since it is really a matter of feel. The excitation force is as light a tap as possible to produce a repeatable value of the resonance frequency. While the initial time to determine an acceptable excitation level may be 5 or 10 minutes, once the operator has a feel for the required excitation, subsequent samples can be tested in seconds.

The flexural response is measured by supporting the specimen at the nodes of its fundamental mode. The selection of a support medium is nontrivial as the specimens should not couple to the supporting medium. Styrofoam cylinders with triangular cross sections were used to support the specimens. The microphone is placed directly beneath the center antinode. The flexural specimens were excited at the center of the specimen (Figure 1).

The longitudinal measurements were taken by lightly holding the specimen edges at midspan, between forefinger and thumb, over the microphone, and exciting the upper end of the beam. This vibration mode was generally more difficult to excite than the flexural mode (Figure 2).

Strength testing was performed on an Instron 1125 universal testing machine at a crosshead speed of 0.02 inches per minute. The specimens were gripped using hydraulic grips with a plasma-deposited finish on the grip face (Surfalloy, MTS, Minneapolis , MN). Strain measurements were made using both single element strain gauges adhesively bonded to the center of the specimen (Micro Measurements P/N CEA-06-375UW-120 or EA-06-250AE-350) and an averaging extensometer (Instron M/N 231 1002 A324-1). Load and strain data were collected using an HP3852 data acquisition unit connected to a Macintosh Centris computer.

RESULTS

The average elastic moduli obtained using impulse excitation, strain gauge (or extensometer) measurements, and those predicted from theory are presented in Table 4. The individual moduli determined for each specimen are presented in Figures 3 through 5 and in Table 3. Extensometer and strain-gauge results are presented as separate data points. Figure 3 contrasts the in-plane modulus determined using the impulse excitation technique to the modulus determined using the strain gauges and/or extensometers. Since the tension-loaded, strain-gauged specimens measure only in-plane stiffness, the strain-gauged data is not compared to the flexural data. Figures 4 and 5 contrast the predicted moduli with the measured moduli.

DISCUSSION

There is good agreement between the impulse excitation results and the strain-gauge (or extensometer) results. The average estimate of variance is ± 5% overall but is much better for several specimen lots. The impulse excitation values of flexural stiffness are generally slightly higher than in-plane stiffness, which is in agreement with that predicted from laminate theory for the laminate stacking sequences interrogated. With the exception of the SP207-1 specimens, the predicted values were lower than the measured values.

The atypical behavior of the SP207-1 specimens is not understood. While optical examination of the plies confirms that the specimens have the specified stacking sequence [0/45/90/-45]2S, small deviations in the ply alignment not discernible visually may account for the lack of agreement. The lack of agreement may also be caused by [0°] laminate having a slightly higher stiffness than reported.

An interesting aspect of the comparison between the vibrational and strain-gauge techniques is the lower scatter observed in the vibrational results. This result would seem to indicate that the scatter typically observed in modulus values determined by using strain gauges is caused by a combination of measurement error and local variations in stiffness. The measurement error may be caused by gauge misalignment, variations in the roughness of surfaces to which the gauge is applied or thickness of the adhesive securing the gauge to the surface. The local variations may be caused by localized clustering of fiber bundles or variations in the distance between the specimen surface and the fibers. Whatever the cause, it appears that the overall stiffness of the laminate is much more consistent than traditional measurements would indicate. This may be an important point when determining statistical allowables for design.

The degree of resolution of the impulse excitation technique makes it attractive as a quality control tool. Comparison between the FUSE-B results and the FUSE-A, FUSE-13 & FUSE-15 results illustrates that subtle differences in laminate orientation can be detected using the impulse excitation technique. The FUSE-B specimens have a [0/30/90/-30]2S stacking sequence, while the FUSE-A, , FUSE-13 & FUSE-15 specimens have a [30/0/-30/90]2S stacking sequence. In plane moduli for both stacking sequences is identical while the flexural moduli for the FUSE-B specimens is substantially different than that of the FUSE-A, , FUSE-13 & FUSE-15 specimens. The difference which ranged from 1.5 to 2.2 Msi between the two stacking sequences agrees with the difference predicted by laminate theory. This degree of resolution makes the impulse excitation technique an attractive tool for quality control testing. Its usefulness is limited because the fundamental frequency of the test specimen must lie within the range of the Grindosonic detection limits. It should be a simple matter to construct tag-end specimens of appropriate dimensions to verify proper laminate sequencing.

While this technique can drastically reduce the cost and time to acquire elastic moduli, the shortcomings of this technique should be noted. The measurement of $[90°]_n$ specimens was attempted without success. The resonance frequency of these specimens, which had nominally the same dimensions as the other specimens, was too low for the acoustic monitor to measure. This was also the problem with very large panels. Measurement of the FUSE square tubes was attempted, also without success. The measurement of shear moduli has not been addressed as yet and may not prove convenient with this equipment.

The acoustic resonance technique is attractive for quick low-cost measurement of the in-plane and flexural moduli. However, it should not be considered a replacement for all mechanical testing. The deflection experienced during excitations of the acoustic resonance specimen are small, so the nonlinearites of large deformations and the differences between tensile and compressive stiffnesses are not addressed. No strength information is obtained from this test technique.

CONCLUSIONS

The impulse excitation method provides a quick and accurate measurement of laminate elastic moduli as an alternative to strain gauges and extensometers. There is minimal setup time, and very little sample preparation is necessary. This technique could prove very useful as an in-process quality control test.

Additional work to determine specimen size-effect and the measurement of shear modulus should be pursued to determine the range of capabilities of the impulse excitation technique to characterize composite materials.

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ACKNOWLEDGMENTS

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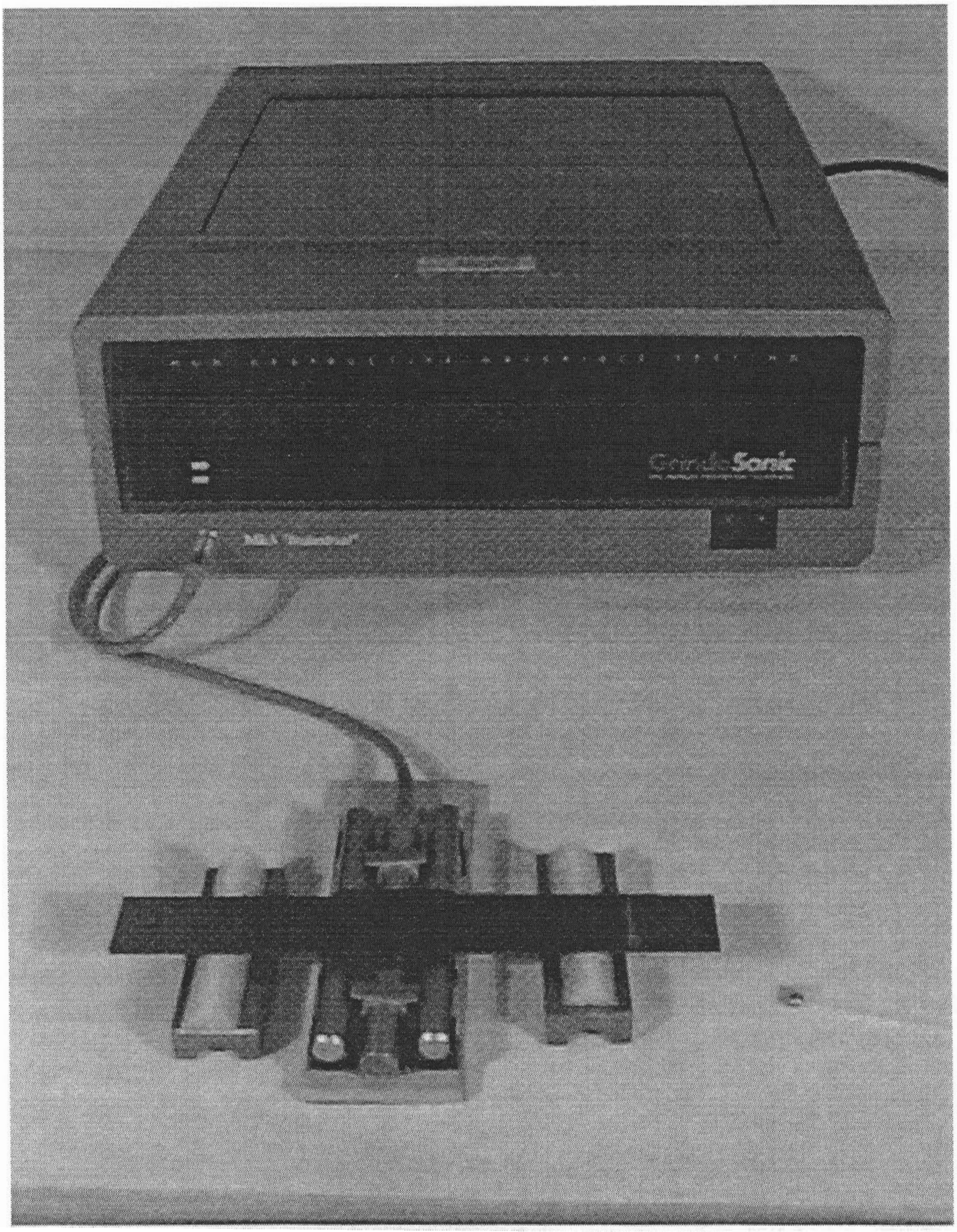

Figure 1. Set up to perform acoustic resonance measurement for flexural bending.

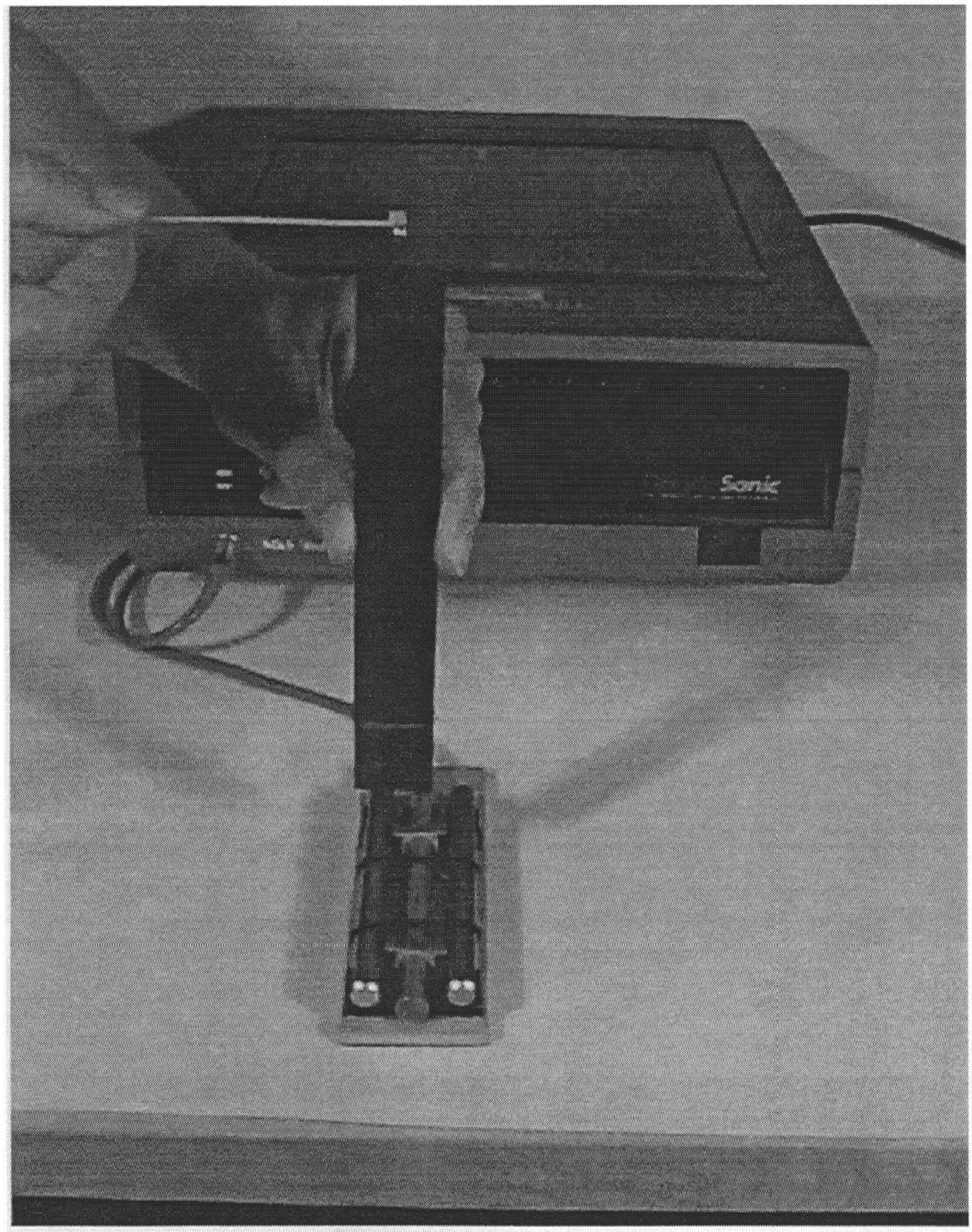

Figure 2. Set up to perform acoustic resonance measurement for in-plane mode.

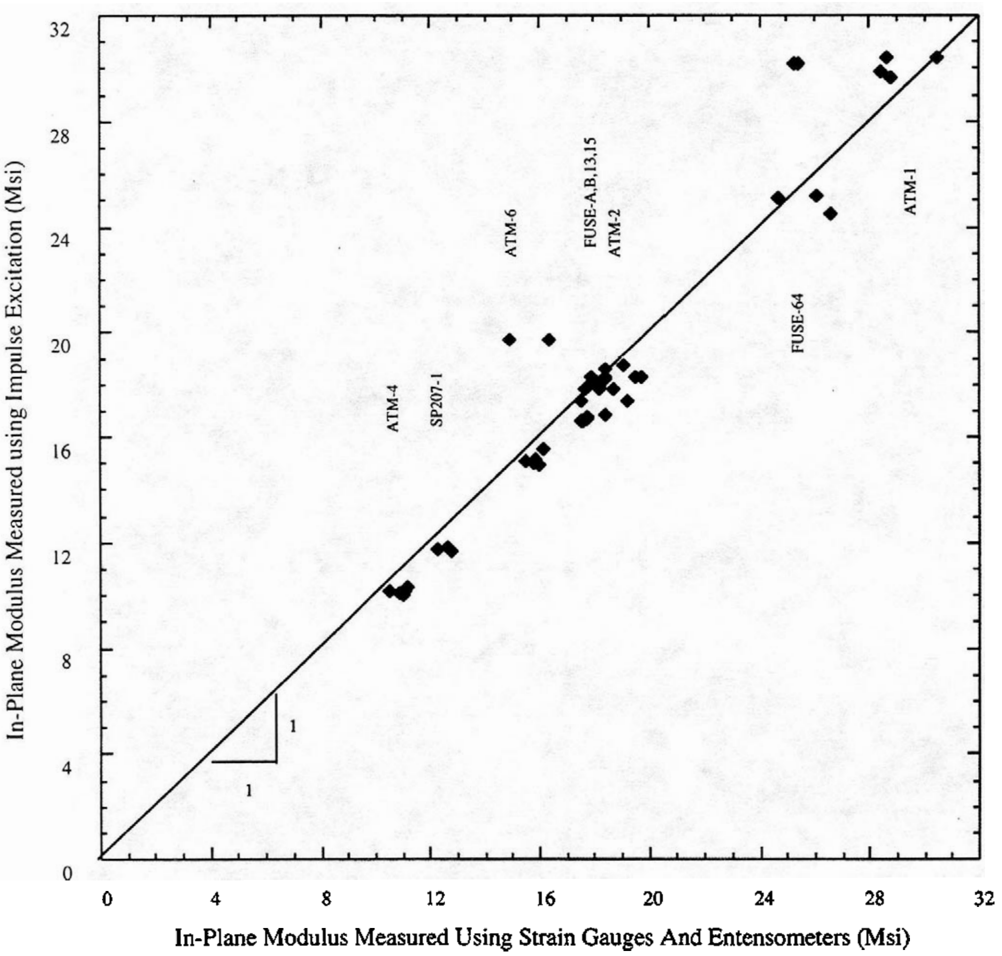

Figure 3. Comparison between tensile moduli determined using strain gauges or extensometers and that measured using in-plane impulse excitation.

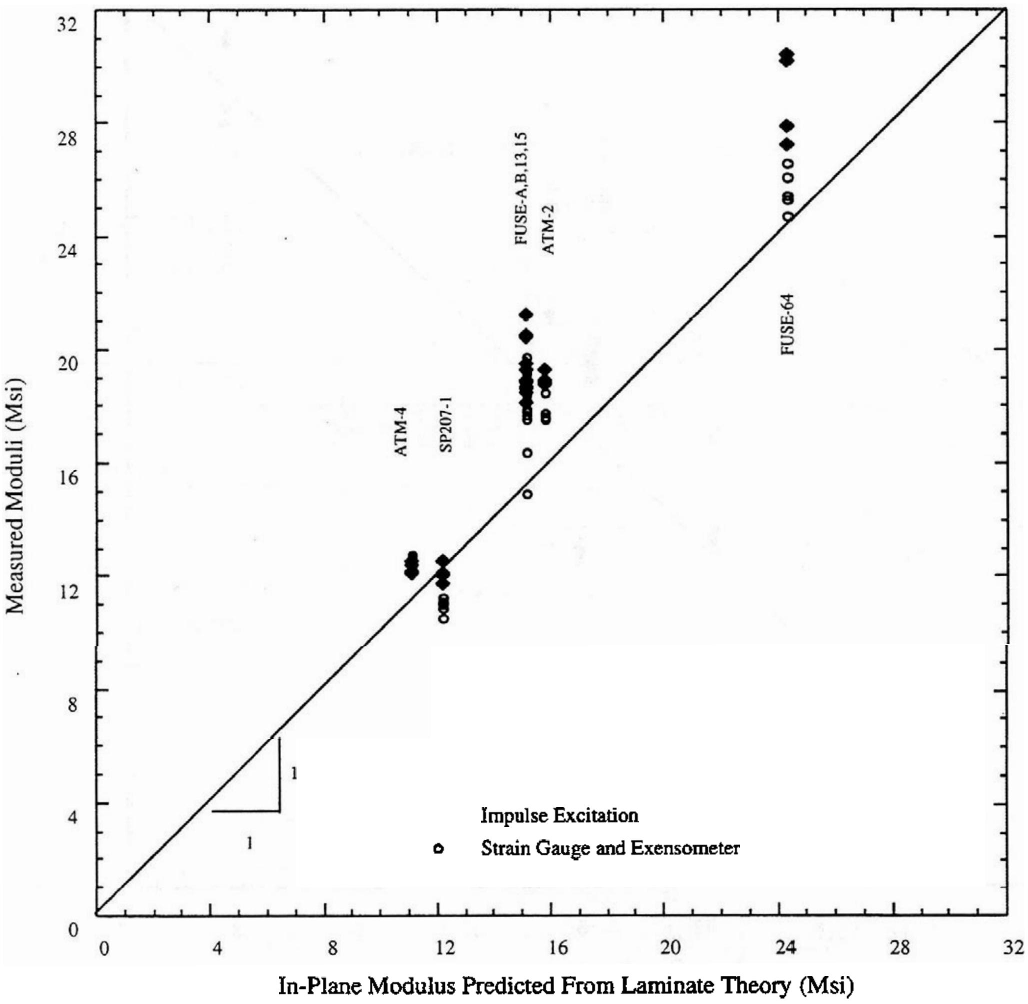

Figure 4. Comparison between tensile moduli determined using strain gauges or extensometers, in-plane impulse excitation technique and that predicted using laminate theory.

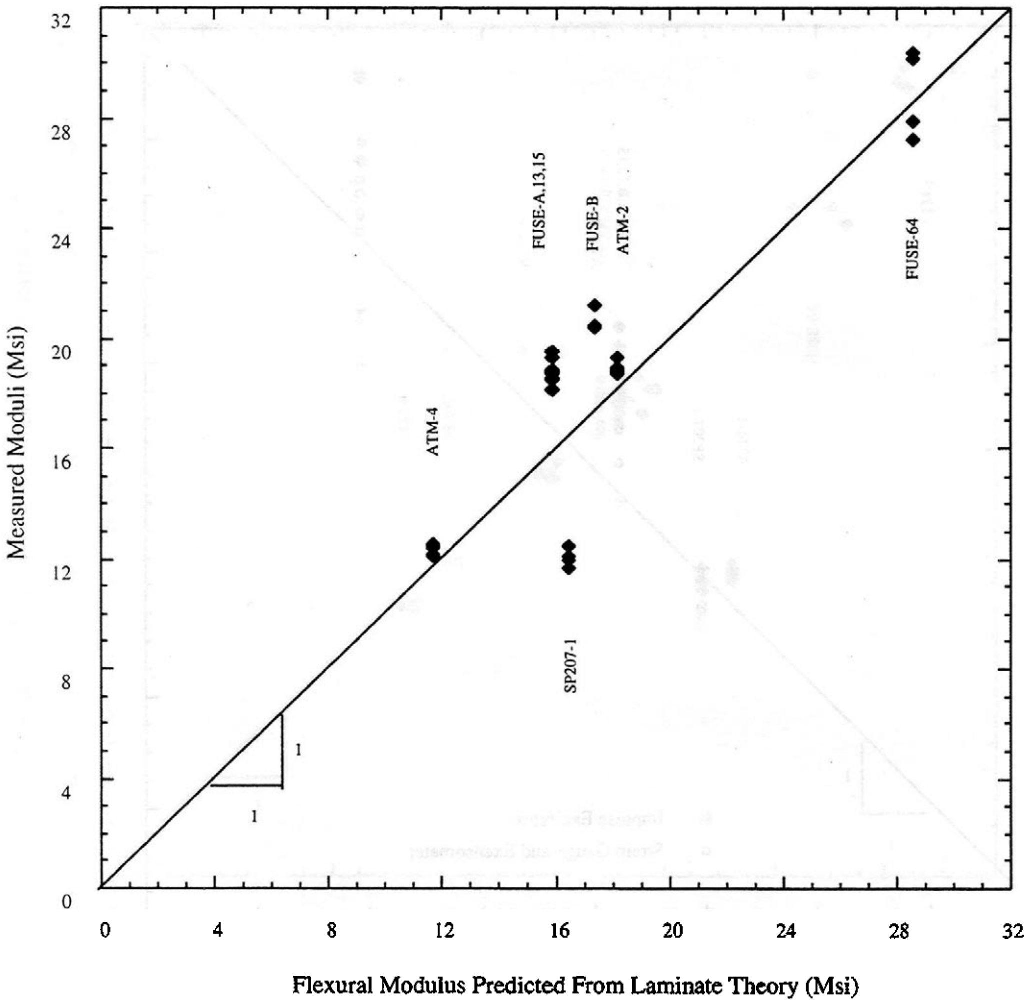

Figure 5. Comparison between tensile moduli determined using flexural impulse excitation technique and that predicted using laminate theory.

Table 1. Manufacturers [0°] Elastic Properties

Prepreg Material Manufacturer-Material	Ex (Msi)	Ey (Msi)	Es (Msi)	ν	Ply Thickness (in)
Amoco T50/1962	37	1.03	0.85	0.28	0.0050
Fiberite T50/934	29	1.03	0.55	0.24	0.0045
Amoco P75/1999	47	1.00	0.85	0.25	0.0045
Fiberite T50/954-2A	34	0.98	0.64	0.24	0.0050

Amoco-Amoco Performance Products Inc., Atlanta, GA
Fiberite-ICI Fiberite, Tempe AZ

Table 2. Laminate Configuration of Specimens

Lot ID	Number of Specimens	Prepreg Material Manufacturer-Material	Ply Orientation
ATM-1	4	Amoco T50/1962	$[0]_{16}$
ATM-2	5	Amoco T50/1962	$[0/30/90/-30]_{2S}$
ATM-4	6	Amoco T50/1962	$[45/0/-45/90]_{2S}$
ATM-6	6	Amoco T50/1962	[Unknown]
FUSE- A	4	Fiberite T50/934	$[30/0/-30/90]_{2S}$
FUSE- B	4	Fiberite T50/934	$[0/30/90/-30]_{2S}$
FUSE-13	4	Fiberite T50/934	$[30/0/-30/90]_{2S}$
FUSE-15	4	Fiberite T50/934	$[30/0/-30/90]_{2S}$
FUSE-64	4	Amoco P75/1999	$[0/60/0/-60]_{2S}$
SP207-1	6	Fiberite T50/954-2A	$[0/45/90/-45]_{2S}$

Amoco-Amoco Performance Products Inc., Atlanta, GA
Fiberite-ICI Fiberite, Tempe AZ

Table 3. Results of Elastic Moduli Measurements

Sample #	Thickness (in)	Width (in)	Length (in)	Mass (g)	Density (g/cc)	R [Flex] (Hz)	R [Long] (KHz)	E [Flex] (Msi)	E [Long] (Msi)	E [Gauge] (Msi)	E [Ext] (Msi)
ATM-1-1	0.079	0.999	9.006	18.227	1.565	444.0	25.07	28.81	29.89	28.39	
ATM-1-2	0.083	1.000	9.006	19.371	1.581	470.0	25.15	29.56	30.4	28.61	
ATM-1-3	0.087	1.001	9.002	20.382	1.587	490.0	24.80	29.29	29.63	28.81	
ATM-1-5	0.088	0.998	9.003	20.566	1.587	499.0	25.11	29.71	30.4	30.47	
ATM-2-1	0.08	1.005	9.001	19.11	1.611	363.0	18.54	19.3	16.82	18.44	
ATM-2-2	0.08	1.005	9.004	18.981	1.600	360.3	18.55	18.9	16.76	17.76	
ATM-2-3	0.08	1.005	9.003	18.994	1.601	358.7	18.5	18.74	16.65	17.51	
ATM-2-4	0.08	1.006	9.003	19.008	1.601	360.4	18.5	18.91	16.64	17.59	
ATM-2-5	0.08	1.005	9.004	18.992	1.601	359.4	18.52	18.82	16.68	17.72	
ATM-4-1	0.079	1.002	9.002	18.78	1.608	289.0	15.57	12.52	11.84	12.62	
ATM-4-2	0.079	1.002	9.002	18.747	1.605	289.0	15.6	12.5	11.86	12.63	
ATM-4-3	0.079	1.003	9.003	18.657	1.606	285.6	15.53	12.38	11.77	12.68	
ATM-4-4	0.078	0.996	9.000	18.353	1.602	281.5	15.55	12.13	11.76	12.27	
ATM-4-5	0.079	1.001	9.001	18.814	1.613	289.1	15.53	12.56	11.81	12.63	
ATM-4-6	0.08	1.001	9.001	18.842	1.595	289.9	15.52	12.18	11.67	12.77	
ATM-6-1	0.087	1.000	8.999	20.289	1.581	359.8	17.74	15.72	15.1	15.83	
ATM-6-2	0.087	1.001	9.000	20.205	1.573	358.0	17.7	15.49	14.96	16.03	
ATM-6-3	0.086	1.001	9.002	19.973	1.573	355.3	17.83	15.62	15.18	15.89	
ATM-6-4	0.086	1.002	9.003	20.076	1.579	355.5	17.69	15.67	15.01	15.79	
ATM-6-5	0.085	1.001	9.003	19.908	1.586	355.0	17.97	16.11	15.56	16.16	
ATM-6-6	0.088	1.002	9.000	20.415	1.570	361.8	17.81	15.43	15.11	15.51	
FUSE-13-1	0.074	1.05	5.397	11.22	1.633	910.6	31.77	18.6	18	-	17.8
FUSE-13-2	0.073	1.115	5.395	11.86	1.649	899.0	31.12	18.8	17.4	17.5	19.2
FUSE-13-3	0.075	1.04	5.397	11.13	1.614	916.0	31.84	18.1	17.8	-	18.2
FUSE-13-4	0.075	1.112	5.399	12.02	1.629	920.6	31.64	18.5	17.8	-	18.7

Table 3 Continued

Sample #	Thickness (in)	Width (in)	Length (in)	Mass (g)	Density (g/cc)	R [Flex] (Hz)	R [Long] (KHz)	E [Flex] (Msi)	E [Long] (Msi)	E [Gauge] (Msi)	E [Ext] (Msi)
FUSE-15-2	0.071	0.996	5.275	9.91	1.622	905.7	32.88	18.1	18.3	18.4	17.9
FUSE-15-3	0.071	1.122	5.276	11.43	1.659	929.0	32.79	19.5	18.6	-	18.4
FUSE-15-4	0.070	0.937	5.292	9.42	1.655	897.0	32.75	18.9	18.6	-	18.4
FUSE-64-1	0.074	1.322	5.725	15.70	1.711	956.4	34.16	27.2	24.5	-	26.6
FUSE-64-2	0.075	0.844	5.745	10.44	1.752	1002	34.02	30.2	25.1	-	24.7
FUSE-64-3	0.072	1.271	5.755	15.5	1.796	950.6	33.67	30.4	25.2	-	26.1
FUSE-64-4	0.073	1.05	5.740	12.67	1.758	938.1	37.31	27.9	30.2	25.3	25.4
SP207-1-H1	0.086	1.003	7.000	14.50	1.469	525.2	19.35	11.7	10.1	10.9	-
SP207-1-H2	0.083	1.004	7.003	14.50	1.518	516.8	19.20	12.5	10.3	11.2	-
SP207-1-H3	0.083	1.004	7.002	14.50	1.513	506.9	19.06	12	10.1	11	-
SP207-1-H4	0.083	1.004	7.000	14.40	1.511	509.5	19.02	12.1	10	11	-
SP207-1-H5	0.084	1.008	7.002	14.50	1.496	525.5	19.27	12.5	10.2	11.1	-
SP207-1-H6	0.085	1.006	7.000	14.60	1.484	527.0	19.36	12.1	10.2	10.5	-
FUSE-A-2	0.072	1.096	5.432	11.51	1.639	894.0	32.17	19.5	18.7	-	19.1
FUSE-A-3	0.073	1.087	5.430	11.63	1.647	886.0	31.42	18.7	17.9	-	18.2
FUSE-A-4	0.071	1.090	5.428	11.45	1.663	871.6	31.56	19.3	18.3	19.7	19.5
FUSE-B-1	0.073	1.032	4.970	10.22	1.654	1132	34.51	21.2	18.2	-	18.4
FUSE-B-2	0.075	1.092	4.965	10.85	1.629	1144	34.38	20.4	17.8	-	17.7
FUSE-B-3	0.075	1.130	4.955	11.24	1.645	1137	36.13	20.5	19.7	14.9	16.4

Table 4A. Measured and Predicted Specimen In-Plane Elastic Moduli (Msi)

Lot #	Average Impulse Moduli	Average Gauge Moduli	Predicted Laminate Moduli
ATM-1	30.08	29.07	-
ATM-2	16.71	17.80	15.79
ATM-4	11.79	12.60	11.05
ATM-6	15.15	15.87	-
FUSE-A	18.30	19.13	15.10
FUSE-B	18.57	16.85	15.10
FUSE-13	18.00	18.48	15.10
FUSE-15	18.50	18.28	15.10
FUSE-64	26.25	25.62	24.29
SP207-1	10.15	10.95	12.19

Table 4B. Measured and Predicted Specimen Flexural Elastic Moduli (Msi)

Lot #	Average Impulse Moduli	Predicted Laminate Moduli
ATM-1	29.34	-
ATM-2	18.93	18.14
ATM-4	12.38	11.73
ATM-6	15.67	-
FUSE-A	19.17	15.84
FUSE-B	20.70	17.33
FUSE-13	18.5	15.84
FUSE-15	18.83	15.84
FUSE-64	28.93	28.54
SP207-1	12.15	16.40