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A COMPARISON OF ULTRASONIC AND MECHANICAL TEST VALUES OF THE PRINCIPAL YOUNG'S MODULUS OF UNIDIRECTIONAL METAL MATRIX COMPOSITES

BY   JOHN V. FOLTZ AND ALBERT L. BERTRAM

RESEARCH AND TECHNOLOGY   DEPARTMENT

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Dahlgren, Virginia 22448-5000 ● Silver Spring, Maryland 20903-5000

FOREWORD

Guided ultrasonic waves can be used to characterize materials. However, there sometimes exists skepticism among engineers as to whether the elastic constants determined by the ultrasonic method agree with the values measured by quasi-static mechanical testing. The work herein is a data summary comparing results of the two test methods for Young's modulus in the fiber direction of several unidirectional metal matrix composite materials.

Approved by:

C. E. Mueller

C.E. MUELLER, Head
Materials Division

ABSTRACT

A method of determining the fiber direction elastic modulus of a thin-ply unidirectional fiber reinforced metal matrix composite using ultrasonic plate waves is described. The results obtained by the ultrasonic technique are compared to values of Young's modulus from mechanical tests on the same materials. The agreement shows that the ultrasonic method is a reliable and essentially nondestructive way of determining Young's moduli in thin unidirectionally reinforced metal matrix composites.

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INTRODUCTION

Metal Matrix Composites (MMCs) are under development for a number of applications. A principal member of the composite family is the lamina with long fibers aligned parallel to one another -- the so-called unidirectional or uniaxial ply. A lamina with this type of fiber layup serves as the basic building block from which the designer develops a more complicated structural laminate. In the case of MMCs, the unidirectional configuration can also be employed as a structural element without cross-plying. Due to the general relevance of the unidirectional ply, a means of nondestructively characterizing its performance features in the fiber direction is of value. Previously, a method was described for determining the elastic constants of MMCs by ultrasonic plate waves.[1] The present work utilizes a similar procedure to obtain Young's modulus in the fiber direction for a number of unidirectional MMCs. The results are compared to the values of Young's modulus obtained from mechanical tension or compression tests on the same materials.

APPROACH

An extensional plate wave which propagates in the fundamental symmetric Lamb mode is introduced into a thin piece of composite material via an ultrasonic transducer in contact with one edge of the material. The transducer used in this work produces a broadband spectrum centered on a frequency of 1/2 MHz, generating waves which roughly satisfy the condition $L/h >> 1$, where

L = wavelength of the ultrasonic wave,
h = thickness of the material,

When $L/h >> 1$ configurational dispersion caused by the plate free surfaces has a minor effect on the ultrasonic wave speed.[2] Consequently, the Young's modulus of the material can be calculated from Equation (1)

$$E_{11} = p\,(V_{11})^2\,R \tag{1}$$

where

E = Young's modulus,
v = wave velocity,
p = density,
11 = subscript to indicate fiber direction,
R = parameter dependent upon Poisson's ratio.

The parameter R is typically in the range of 0.94 to 0.99 for most unidirectional MMCs. R is discussed in the Appendix.

The form of the MMC specimens was either flat plate, strips of panels, or simple structural elements such as tubes, C-sections, or L-sections. In all cases the specimens were much thinner than the wavelength of the ultrasonic wave and were oriented so that the wave propagated in the fiber direction. The speed of the wave was measured using a through-transmission approach with a delay block of either PMMA or Al. A fiducial mark was obtained on an oscilloscope screen by sending an ultrasonic pulse through the delay block and into a receiving transducer that was identical to the transmitting transducer. A similar procedure was followed with the specimen in place on the delay block and the temporal displacement of the oscilloscope signal, which corresponded to the transit time of the pulse through the specimen, was read directly from the face of the screen. The plate wave velocity was calculated from the specimen length and the transit time. This information, together with a value for density obtained from specimen weight and geometry and an estimated value of R, permitted E_{11} to be calculated via Equation (1).

TEST RESULTS

Fifteen specimens of graphite fiber reinforced aluminum (Gr/Al) were fabricated at the Naval Surface Warfare Center using precursor material obtained from the Celanese Corporation, Summit, New Jersey. The precursor material was a flexible tow of 12,000 graphite filaments which were coated with Al by an ion-plating process. The fiber, sans Al, has the trade name Besfight HT-7-12000, a diameter of 0.28 mil and a Young's modulus of 30 MSI. The Al-coated tow was consolidated in a hot-press into rectangular strips of panel 107 to 115 mm long (the length is the fiber direction), approximately 18 mm wide and 1 mm thick. The strips had a nominal fiber fraction of 40 percent by volume. As part of the fabrication study, consolidation time in the press was deliberately varied over the specimen set with the result that some specimens were not fully densified. The plate wave velocity was determined in the fiber direction for each sample and is given in Table 1; in general, it is seen to be slightly more than 7 mm/μsec. Using this value and the equation

$$V = fL \qquad (2)$$

where $f = 1/2$ MHz, the wavelength L is calculated to be 14 mm. The ratio of wavelength to panel thickness in these strips is therefore on the order of 14 to 1, i.e., $L/h = 18$. The ultrasonic Young's modulus was calculated using Equation (1) with an estimated value of $R = 0.98$. Each strip was then subjected to a tension test in an Instron Universal Testing Machine to determine the mechanical value of Young's modulus.[3] All data pertaining to this set of specimens are presented in Table 1.

Three 1/2-inch wide by 6-inch long by 1/10-inch thick stips of aluminum oxide fiber reinforced aluminum (known as FP/Al) were available as residual samples from another project. Ultrasonic and tensile test modulus determinations were conducted on a one-to-one basis and the data are given in Table 2. R was calculated from Equation (A-8). For these samples $L/h = 6.7$.

Several unidirectional fiber panels of Gr/Al, graphite fiber reinforced magnesium (Gr/Mg), graphite fiber reinforced copper (Gr/Cu), boron filament reinforced aluminum (B/Al), and silicon carbide reinforced aliminum (SCS/Al) were also evaluated. The panels were dedicated to other experiments as well as the present one and therefore could not be consumed entirely in this work. Ultrasonic wave speeds were determined in a manner thought to provide a representative value for a given panel. Subsequently, tensile tests were conducted on strips cut from the same panel. Panel descriptions and test results are summarized in Table 3. Each tensile test value listed is the average of at least two tests. The panel thicknesses ranged from 25 mil to approximately 100 mil. The value of R in Table 3 was calculated from Equation (A-5).

The ultrasonic approach to modulus determination was also evaluated for three types of simple structural elements (strut-type members) made of unidirection Gr/Al.

TABLE 1. ION-PLATED GR/AL TEST RESULTS

SPECIMEN NUMBER	DIMENSIONS AT TEST		DENSITY* GM /CC	V (AX) (mm/μsec)	E $_{11}$ (MSI)	
	WIDTH* (INCH)	THICKNESS* (INCH)			PLATE WAVE VALUE	TENSILE TEST*
1	0.508	0.042	1.996	7.172	14.48	16.39
2	0.442	0.031	2.366	7.154	17.00	14.42
3	0.517	0.037	2.046	7.111	14.56	15.45
4	0.561	0.041	1.872	7.255	13.86	12.85
5	0.554	0.036	2.042	7.240	15.09	15.36
6	0.563	0.036	2.100	7.222	15.40	15.46
7	0.558	0.035	2.053	7.181	14.87	17.55
8	0.578	0.040	2.127	7.254	15.73	16.09
9	0.580	0.033	2.180	7.214	15.91	15.26
10	0.617	0.032	2.161	7.198	15.71	16.57
11	0.612	0.032	2.208	7.260	16.37	18.24
12	0.625	0.030	2.335	7.194	16.87	15.99
13	0.590	0.033	2.127	7.187	15.41	14.76
14	0.560	0.037	2.075	7.242	15.22	15.59
15	0.589	0.042	2.128	7.189	15.76	17.61
AVERAGE					15.48	15.84

* DATA FROM REF (3)

TABLE 2. FP/AL TEST RESULTS

SPECIMEN NUMBER	V_F (AX) (mm/μsec)	V_F (TR) (mm/μsec)	R	E_{11} (MSI)	
				PLATE WAVE VALUE	TENSILE TEST VALUE
7795-104-69	8.65	6.38	0.95	33.4	32.4
7795-104-70	8.55	6.48	0.95	32.6	31.2
7795-104-76	8.55	6.69	0.94	32.3	31.6
AVERAGE				32.8	31.7

COMPOSITE VENDOR: DUPONT

FAB. PROCESS: VACUUM METAL INFILTRATION

FIBER TYPE: Al_2O_3

MATRIX ALLOY: Al-2LI

DENSITY: 3.24 Gm/cm^3

TABLE 3. DESCRIPTION OF UNIDIRECTIONAL MMC PANELS AND TEST RESULTS

MMC VENDOR	PANEL IDEN. NO.	TYPE MMC	FAB. PROCESS	FIBER TYPE	MATRIX ALLOY	DENSITY (gm/cm³)	THICKNESS (mm)	VF (AXIAL) (mm/µsec)	VF (TR) (mm/µsec)	R	E (MSI)	
											PLATE WAVE VALUE	TENSILE TEST VALUE
DWA	G5198	GR/AL	A	P55	6061	2.39	2.18	8.78	3.58	0.98	26.1	27.5
DWA	G4509	GR/AL	A	P55	A201	2.49	1.22	8.07	3.76	0.98	23.0	25.4
DWA	G4584	GR/AL	A	P100	6061	2.41	1.07	11.3	3.06	0.99	43.9	41.8
MCI	PBR10	GR/MG	B	P55	AZ91C	1.87 (b)	1.19	8.01	3.68	0.98	17.1	17.1
DWA	G5313	GR/MG	A	P100	AZ91C	1.88 (a)	0.61	12.2	3.59	0.99	40.2	41.5
AVCO	81-257A	B/AL	C	5.6 mil B/W	6061	2.54	0.76	9.71	7.50	0.95	33.0	31.7
AVCO	81-457	SIC/AL	D	SCS-2	6061	2.82	0.81	8.84	6.80	0.95	30.3	29.2
DWA	G5100	GR/AL	A	GY70	A201	2.52	0.66	8.84	3.88	0.98	28.0	28.0
DWA	G5232	GR/CU	A	P55	113	4.95 (b)	1.45	6.26	2.38	0.99	27.8	25.2

A. LIQUID METAL INFILTRATION + DIFFUSION BONDING
B. LIQUID METAL INFILTRATION + HOT ROLLING
C. DIFFUSION BONDING
D. PLASMA SPRAYED + CONSOLIDATED

(a) ESTIMATED VALUE
(b) DIMENSIONAL + WEIGHT VALUE

The fiber reinforcement is a pitch-based type known as P55 with a nominal diameter of 10 micron and nominal modulus of 55 MSI. Hardware fabrication was performed by Fiber Materials, Inc. (formerly Material Concepts, Inc.), of Columbus, Ohio, using a pultrusion process. Cross-sectional views of the three shapes are shown in Figure 1. Wave speeds in the fiber direction were determined over the full specimen length. The value R = 0.98 was used. The struts were subsequently tested to failure in axial compression with the ends fully restrained against rotation. Testing was performed by Measurements Technology, Inc., Roswell, Georgia. Eighteen specimens were tested overall. From the slenderness ratio (length/radius of gyration) all struts were classified as short columns, thus indicating that plastic failure would precede stability failure. Tables 4, 5, and 6 give the density and test results for the structural members.

UNITS: INCH

WALL = 1/16
LNGTH = 6

13/16

7/8

C-SECTION

WALL = 1/16
LENGTH = 7

3/4

3/4

L-SECTION

LENGTH = 8

3/5

1/2
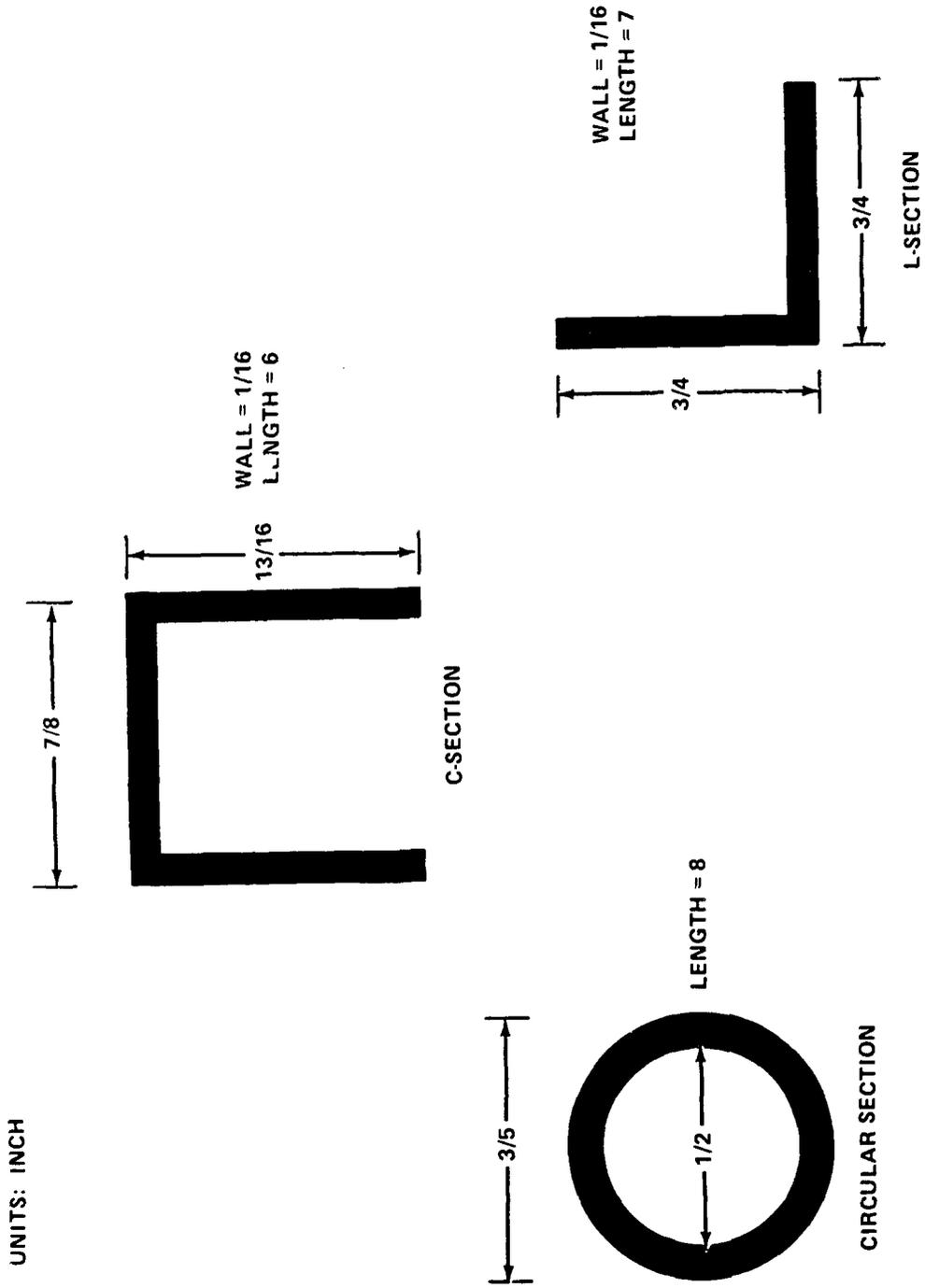
CIRCULAR SECTION

FIGURE 1. NOMINAL GEOMETRY PARAMETERS FOR P55/6061 STRUCTURAL ELEMENTS

TABLE 4. GR/AL CIRCULAR SECTION TEST RESULTS
$p = 2.40 \, gm/cm^3$

SPECIMEN NUMBER	V_F (AX) (mm/μsec)	E_{11} (MSI)	
		PLATE WAVE	COMPRESSION TEST
336-8A	8.70	25.8	23.1
336-15	8.56	25.0	25.5
336-9	8.62	25.3	23.5
100-43	8.66	25.6	24.9
336-8B	8.85	26.7	23.6
AVERAGE		25.7	24.1

TABLE 5. GR/AL C-SECTION TEST RESULTS
$p = 2.41 \, gm/cm^3$

SPECIMEN NUMBER	V_F (AX) (mm/μsec)	E_{11} (MSI)	
		PLATE WAVE	COMPRESSION TEST
593B	8.64	25.6	24.8
592A	8.54	25.0	22.6
590	8.68	25.8	23.9
588	8.71	26.0	23.6
591	8.80	26.5	24.3
592	—	—	29.7
AVERAGE		25.6	24.8

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TABLE 6. GR/AL L-SECTION TEST RESULTS
p = 2.41 gm/cm^3

SPECIMEN NUMBER	V_F (AX) (mm/μsec)	E_{11} (MSI)	
		PLATE WAVE	COMPRESSION TEST
584-6	8.61	25.4	26.8
584-5	8.60	25.0	25.1
583-7	8.55	25.0	32.2
584-4	8.55	25.3	24.8
585-1	8.66	25.7	23.4
585-5	8.68	25.8	22.7
AVERAGE		25.4	25.8

ANALYSIS

In Figure 2 the ultrasonic values for Young's modulus are plotted against the mechanical test values for all experiments conducted. The points shown are the average moduli of Tables 1, 2, 4, 5, and 6 and all the moduli of Table 3. Perfect agreement would be exhibited by the points lying on a straight line through the origin inclined at 45° to the axes. A straight line

$$E_{11U} = A + B E_{11M} \tag{3}$$

where E_{11U} is the ultrasonic test modulus and E_{11M} the mechanical test modulus, was fit to this data by the method of least-square-errors as applied to a Gaussian distribution. All statistical methods used in this report are described by Bevington.[4] A and B are constants to be determined from the curve fitting procedure. For perfect agreement between the test results:

A = 0 MSI, B = 1 MSI⁻¹.

The analysis yields:

A = (-0.4 ± 1.6) MSI,

B = (1.03 ± 0.06) MSI⁻¹

(the uncertainty is one standard deviation). The agreement is within the uncertainty of the experiments.

The linear-correlation coefficient, r, was used to further investigate this agreement. This coefficient is a statistical parameter which provides a measure of the degree of linear correspondence that exists between two observed quantities. The absolute value of r ranges from 0, when there is no correlation, to 1, when there is one hundred percent correlation. The r for the data set of Figure 2 was calculated as r = 0.98, indicating that a high correlation between the two test methods exists.

The probable error, P.E., is a quantity calculated from a data set which gives an estimate of the uncertainty in the dependent variable over the data set as a whole. For the data set of Figure 2, the P.E. = 0.98 MSI. That is, an ultrasonic determination of Young's modulus should lie within approximately one MSI of the mechanical test value for any material tested.
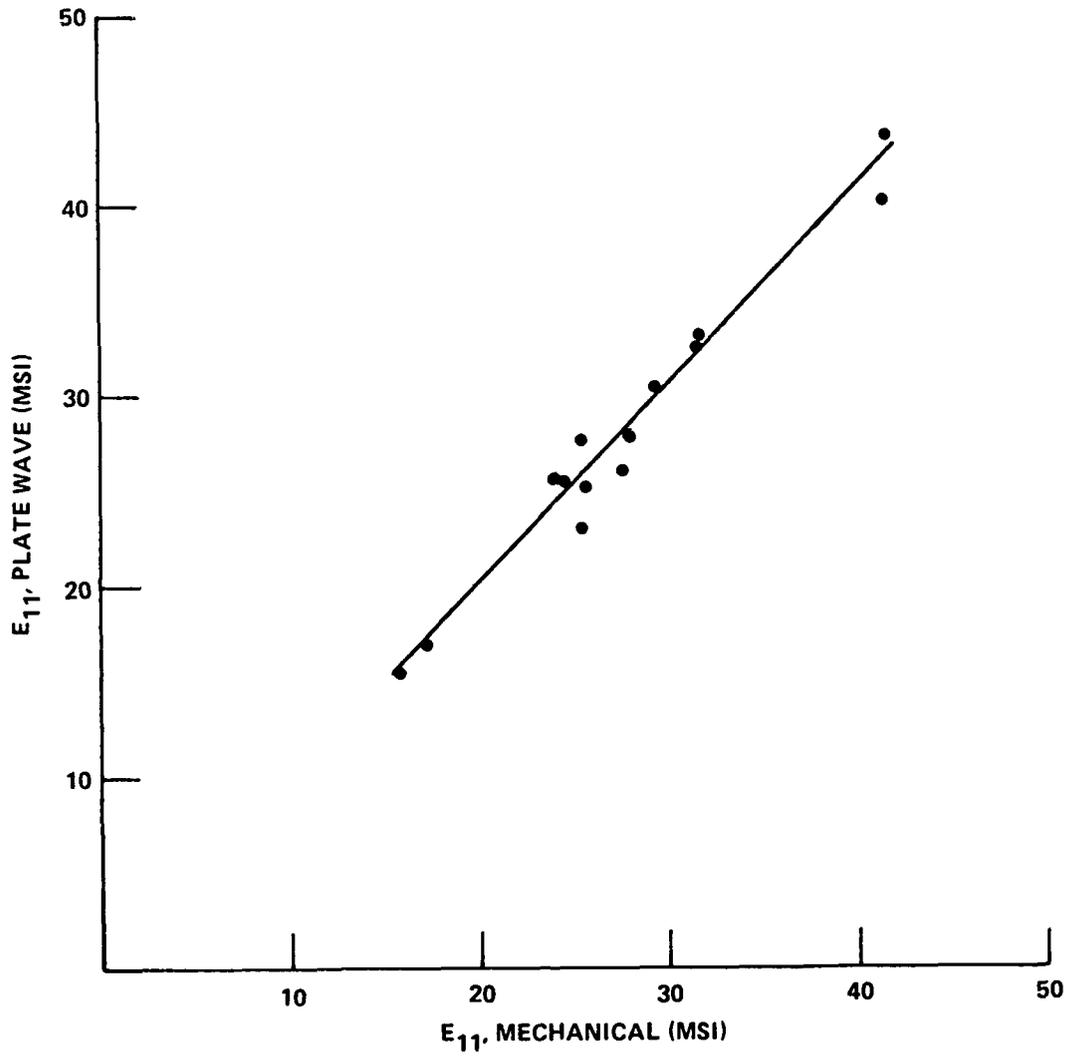
FIGURE 2. PLATE WAVE AND MECHANICAL TEST VALUES OF
YOUNG'S MODULUS FOR UNIDIRECTIONAL MMCS

CONCLUSIONS

The ultrasonic values of Young's moduli correlated well with the mechanical test results for a variety of unidirectional MMCs. The discrepancy between the moduli determined by the two methods is approximately one MSI. Therefore, the ultrasonic method is deemed reliable for determining Young's moduli in these unidirectionally reinforced MMCs.

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APPENDIX

The parameter R is given by the expression [A-1]

$$R = 1 - v_{12} v_{21} \qquad (A-1)$$

where the v_{12} and v_{21} are the major and minor Poisson ratios of the unidirectional lamina.[A-1]

$$v_{21} = v_{12} E_{22}/E_{11} \qquad (A-2)$$

E_{11} and E_{22} are the lamina moduli in the fiber and transverse directions, respectively. The ratio of moduli may be determined if the ultrasonic wave speeds are known in both the fiber and transverse directions,[A-2]

$$E_{22}/E_{11} = (V_{22}/V_{11})^2 \qquad (A-3)$$

Then Equation (A-1) becomes

$$R = 1 - (v_{12} V_{22}/V_{11})^2 \qquad (A-4)$$

The second term on the right-hand side of Equation (A-4) is much smaller than the first. A reasonable estimate of v_{12} for the present MMCs is 0.3. Then

$$R = 1 - (0.09)(V_{22}/V_{11})^2 \qquad (A-5)$$

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