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A DETERMINATION OF THE ZERO DEGREE ELASTIC MODULI AND COMPRESSI--ETC(U)
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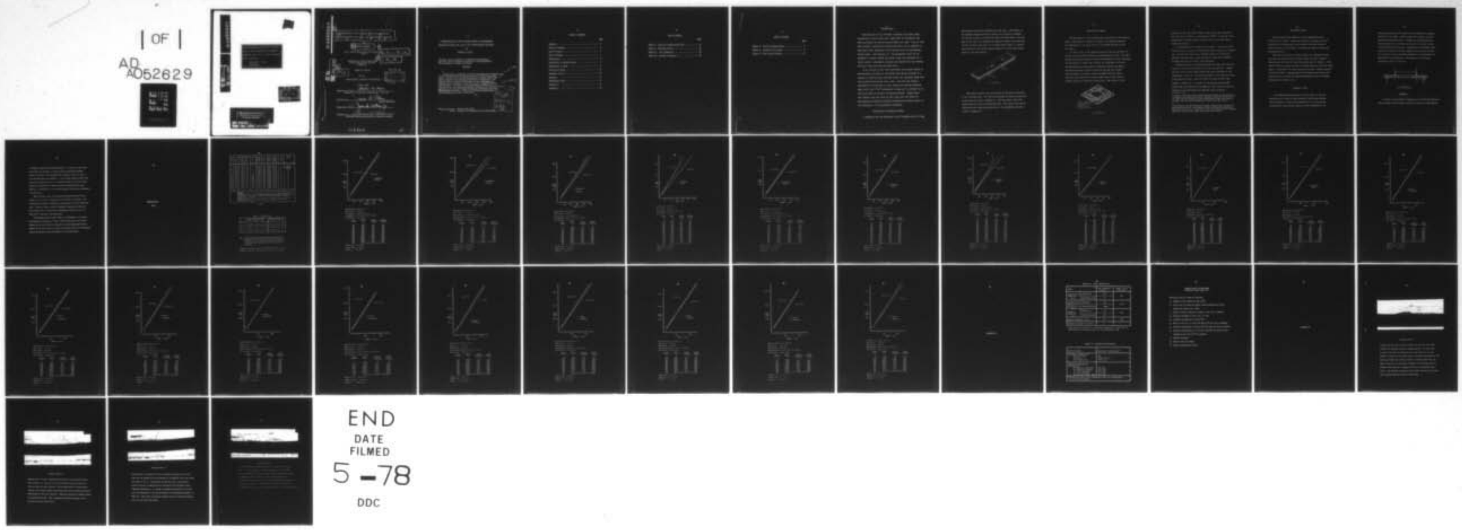

A DETERMINATION OF THE 0° ELASTIC MODULI AND COMPRESSIVE ALLOWABLE STRENGTH FOR 2-PLY, $0\text{-}90^{\circ}$ GRAPHITE EPOXY LAMINATE

Douglas M. Hoon
Course II
May 1976

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A DETERMINATION OF THE 0° ELASTIC MODULI AND COMPRESSIVE ALLOWABLE STRENGTH FOR 2-PLY, 0-90° GRAPHITE/EPOXY LAMINATE.

by

(10) DOUGLAS M. HOON

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by

DOUGLAS M. HOON

Submitted to the Department of Mechanical Engineering on 1 May, 1976 in partial fulfillment of the requirements for the Degree of Master of Science.

ABSTRACT

Little data is currently available concerning the properties of thin graphite/epoxy laminates supported by low density foam cores. To help fill this information gap a testing program has been initiated at Massachusetts Institute of Technology. The testing method, including preparation of test specimens, is outlined and the results of the first tests of 0-90° laminates are presented. Analysis of the test results is limited to calculation of the Normal Distribution parameters for the 0° elastic moduli and the Weibull Distribution parameters for the 0° compressive strength. Methods of failure are documented with photographs and explanatory text.

ZERO TO 90 DEGREE

ZERO DEGREE

Thesis Supervisor: James W. Mar, Sc.D.
Title: Professor of Aeronautics and Astronautics

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Introduction

The potential of the advanced composites have been widely recognized in recent years and a great deal of information has been accumulated by various manufacturers and users. Most of this data, however, describes the properties which can be expected in relatively thick laminates (10-100 plies) after the recommended curing cycle. (See Appendix A.) The properties which can be expected in lightly loaded structures using thin laminates (1-3 plies) cured at atmospheric pressure and supported by low density (3-6 pcf) foam cores are less well known.

In an attempt to fill this information gap several people at Massachusetts Institute of Technology have become involved in a program of testing single graphite fibers and composite beams with thin graphite facings and foam cores. The work that follows represents the first step in that program for testing composite beams with 2-ply 0°-90° orientation facings and is believed to be the first study of its kind conducted anywhere. Twenty beams were tested using two types of foam cores with the intent of determining compressive allowable strengths and elastic moduli of the laminates in the longitudinal direction.

Description of Composite Beams

A composite beam as discussed in the following work is a beam constructed with graphite facings and a foam core. (See Figure 1.) The graphite facings provide the tension and compression strength of the beam as well as providing the beam resisting moment. The purpose of the foam is to separate the graphite facings, give continuous support to prevent buckling, and to resist shear forces. To prevent local failure at the loading points mahogany end blocks were substituted for the core material.

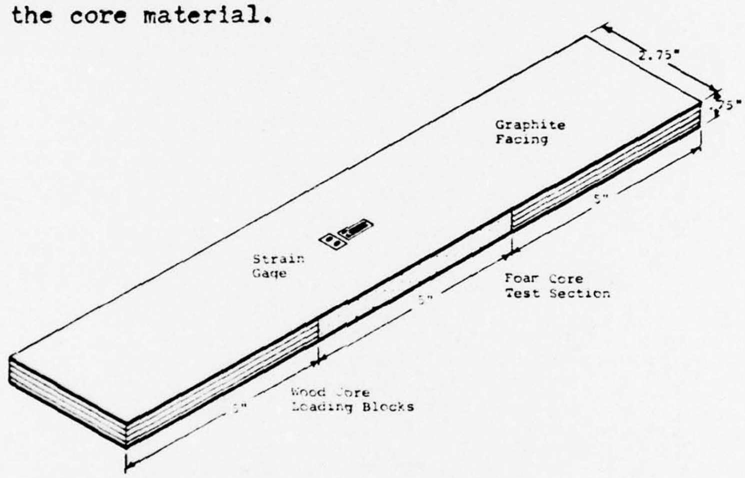

Figure 1
Typical Composite Beam

The graphite material was manufactured by Hercules Incorporated in 12" pre-preg tapes. The various mechanical and physical properties of the tape are listed in Appendix A. The foam used in the first eight beams was Upjohn's CPR Urethane Foam. That used in the last 12 beams was Airex Polyvinyl Chloride Foam. Foam properties are also listed in Appendix A.

Preparation of Beams

The fabrication of each composite beam consisted of three distinct steps. These were: (1) curing and sizing of the graphite laminate; (2) preparation of the core; and (3) the secondary bonding of core and facing.

The preparation of the graphite facing was the most difficult as well as the most important step in the construction process. The temperature during cure appeared to make some difference in final properties and the measure of vacuum was important in determining the quality of interlaminar bonding as well as laminate thickness and weight. The layup procedure involved placing the pre-preg tape between blotting layers (fiberglass cloth) and release material (peel-ply cloth) and mounting the several layers upon a steel plate to prevent crushing or distortion during cure. (See Figure 2.) The

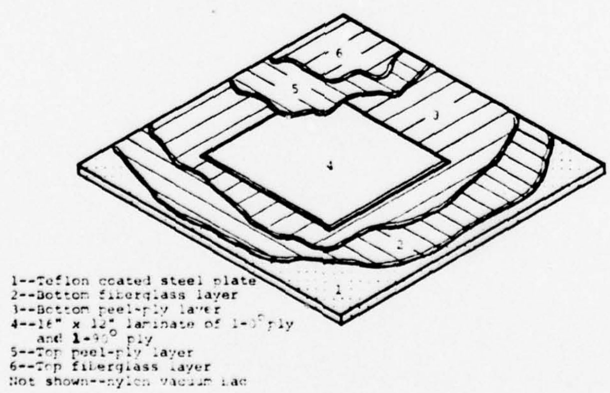

FIGURE 2

Graphite Curing Layup

entire layup was then sealed inside a nylon vacuum bag, evacuated, and cured for 2½ hours at a temperature of 350°F.* At the end of its curing cycle the large sheet of laminate was cut to proper size on a sheet-metal shear.

The preparation of the core was much easier. The wood and foam blocks were cut to size on a table saw and glued together in a special jig. The core was then put on a milling machine to produce flat, parallel facing surfaces. Light sanding to remove any roughness or fuzziness was the last step in core production.

Secondary bonding was necessary because the foam cores could not withstand the high temperatures used to cure the graphite. Bonding was done using Smooth-On EA-40 epoxy under vacuum pressure at room temperature. The vacuum bag layup was similar to the graphite curing layup described above. After the epoxy had cured the beams were resized to adjust for any slippage of the graphite during cure.** Excess epoxy was sanded from the edges on a belt sander and from the surfaces to be instrumented with #220 wet or dry sandpaper.

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* Various other temperature cycles were tried early in the program in an attempt to reduce the laminate thickness toward the nominal value of .0052" per ply obtained by the manufacturer during high pressure curing. For the various temperature cycles tried see Table 1.

** The graphite facings frequently slipped sideways such that part of the graphite would be unsupported while a corresponding portion of the core would be bare. Resizing was done on a power sander to adjust beam width such that uncovered core areas were removed.

Testing Procedure

The beams were instrumented with Micro Measurement EA-13-187BB-120 Strain Gages. Gages were placed on both faces in the 0° orientation and were placed at the center of the beam facings to reduce any edge or end effects. No attempt was made to measure the transverse strain.

The beams were tested for their tension and compression moduli and their compressive failure strength using four-point loading. A Baldwin-Emery SR4 Model FGT test machine was used for loading. A BLH Type 20 strain indicator was used to measure strains on the first eight beams. A BLH Model 1200 strain indicator was used to measure strains on the last twelve. Loading steps of 20-50 pounds were used so that observations of the beam and several measurements could be recorded throughout the loading cycle.

Analysis of Data

The loading geometry was such that the moment in the test section was 1.38 times the load applied by the testing machine. The beam moment of inertia was determined as for a rectangular cross-section using average facing and core thicknesses at the strain gage centerline and ignoring the contribution to bending stiffness of the foam. Stresses were then computed using the familiar relationship S=My/I. Tension and compression moduli were determined by calculating the slope of the linear portion of the stress-strain diagrams. Calculation of the Weibull parameters for compressive failure strength was done with the help of a computer program previously developed in the Department of Aeronautics and Astronautics. The geometry of the loading mechanism is shown in Figure 3.

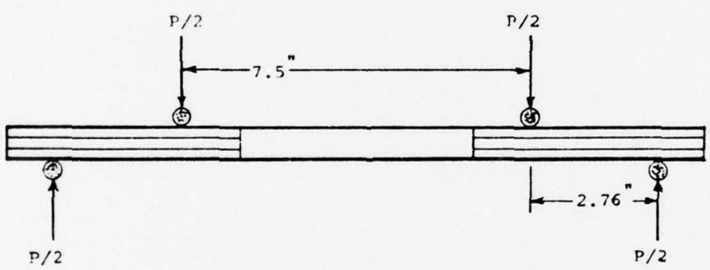

Figure 3
Beam Loading Geometry

Findings

In light of these tests it appears that the Polyvinyl Chloride Foam may offer core properties which will satisfy the requirements of lightly loaded composite structures. It is easy to work with and allows the laminate to develop good compressive strength without buckling. The Urethane Foam, however, does not seem to be a satisfactory core material. In all cases where urethane was used beam failure was due to a tension failure of the foam which allowed the graphite to buckle outward at relatively low beam loading. Photographs of the various modes of failure are presented in Appendix B.

With PVC foam cores the laminate demonstrated mean elastic moduli of 7.38 MSI in compression and 7.59 MSI in tension. The compressive allowable strength was calculated to be 272 pounds per inch. Modes of failure were an apparent compressive failure of the graphite and a combination compression failure of both the foam and the graphite simultaneously.

The testing methods used appear, in retrospect, to be sound and should be continued as such. Future testing may well yield higher moduli and allowable strength as additional experience is gained and if more attempt is made to closely follow the recommended curing temperature cycle published by the manufacturer.

EXPERIMENTAL DATA

Beam #	Core properties: Width (in)	Thickness (in)	Length (in)	Material	Average facing thickness (in)	N max (lb/in)	Tension modulus (10^6 psi)	Compression modulus (10^6 psi)	Failure mode	Curing Cycle
1	2.62	.767	5.1	U	.0132	234	7.41	7.04	a	Unknown
2	2.65	.771	5.1	U	.0135	170	6.60	5.72	a	Unknown
3	2.62	.765	5.1	U	.0129	221	7.63	6.83	a	Unknown
4	2.65	.772	5.1	U	.0172	334	6.37	8.00	a	a
5	2.59	.766	5.1	U	.0142	223	6.92	7.22	a	b
6	2.65	.779	5.1	U	.0148	279	7.41	7.58	a	b
7	2.69	.781	5.1	U	.0176	293	6.08	7.63	a	c
8	2.62	.764	5.1	U	.0185	327	6.15	6.15	a	c
9	2.47	.721	5.0	PVC	.0153	642	7.33	7.33	b	d
10	2.66	.693	5.0	PVC	.0153	554	7.17	6.78	b	d
11	2.49	.682	5.0	PVC	.0143	507	7.63	7.66	b	e
12	2.40	.730	5.0	PVC	.0145	456	7.14	7.35	c	e
13	2.65	.692	5.0	PVC	.0143	469	8.16	7.55	b	e
14	2.65	.715	5.0	PVC	.0144	461	7.69	7.60	b	e
15	2.64	.710	5.0	PVC	.0138	366	7.66	7.37	c	e
16	2.64	.669	5.0	PVC	.0140	517	7.78	8.10	c	e
17	2.68	.714	5.0	PVC	.0145	513	7.56	7.22	c	e
18	2.49	.705	5.0	PVC	.0138	510	7.53	7.14	d	e
19	2.57	.704	5.0	PVC	.0136	419	7.63	7.49	c	e
20	2.57	.705	5.0	PVC	.0142	520	7.91	6.94	c	e

Notes:

Material--U designates Upjohn's 9006-4 Urethane; PVC designates Airex Polyvinyl Chloride.

Failure mode--"a" is tension failure of the foam; "b" is compression failure of the graphite facing; "c" is combination failure of both foam and graphite in compression; "d" is compression failure of graphite originating at site of earlier ply delamination.

Curing Cycles--"a" is 2.75 hrs @ 350°F; "b" is 3 hrs @ 250° and 1 hr @ 350°; "c" is 3 hrs @225°, 1 hr @ 350°; "d" is 2.5 hrs @225°, 1.75 hr @ 350°; "e" is 2.5 hrs. @ 350°F.

TABLE 1

TABLE 2 STATISTACAL DATA

Beams	Normal Distribution Parameters for Elastic Moduli (MSI)				Weibull Parameters for Compressive Strength		
	μ_{E_c}	σ_{E_c}	μ_{E_t}	σ_{E_t}	$\hat{\alpha}_N$	$\hat{\beta}_N$	f_B
1-8	7.02	.77	6.82	.61	5.62	282.0	.35
9-20	7.38	.35	7.59	.29	7.66	523.7	.52

Note: N_B, the design allowable compressive load per inch, is calculated from the above as $N_B = f_B \times \hat{\beta}_N$ and represents that value of N such that 90% of all samples (future) will fail at some load greater than or equal to N_B with 95% confidence.

COMPRESSIVE ALLOWABLE STRENGTH WITH URETHANE FOAM CORE: 98 lb/in.

COMPRESSIVE ALLOWABLE STRENGTH WITH PVC FOAM CORE: 272 lb/in.

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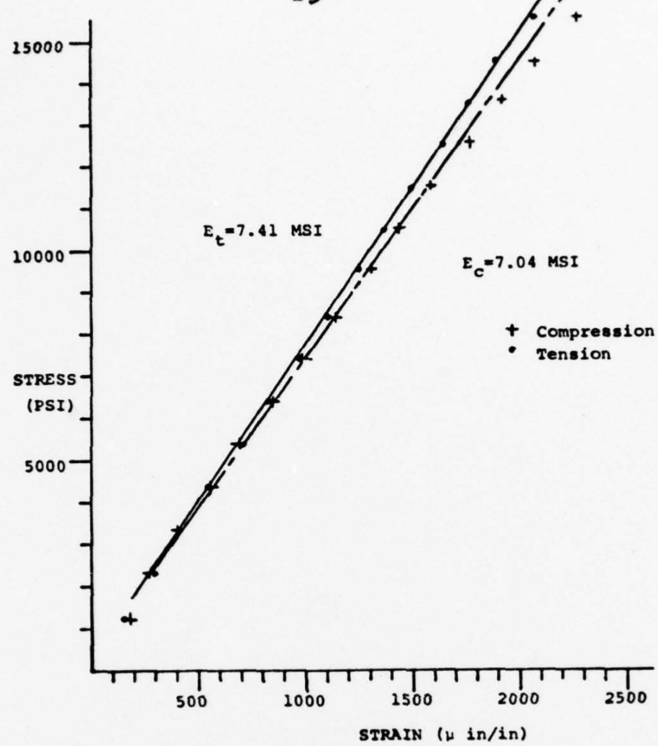


SPECIMEN NUMBER: 1-MOON BEAM #1

DATE OF TEST : 15 DEC 75

CORE MATERIAL : CPR URETHANE 9006-4

CORE DIMENSIONS: 0.767 X 2.620 X 5.100 INCHES

PLY THICKNESS : 0.0132 INCHES

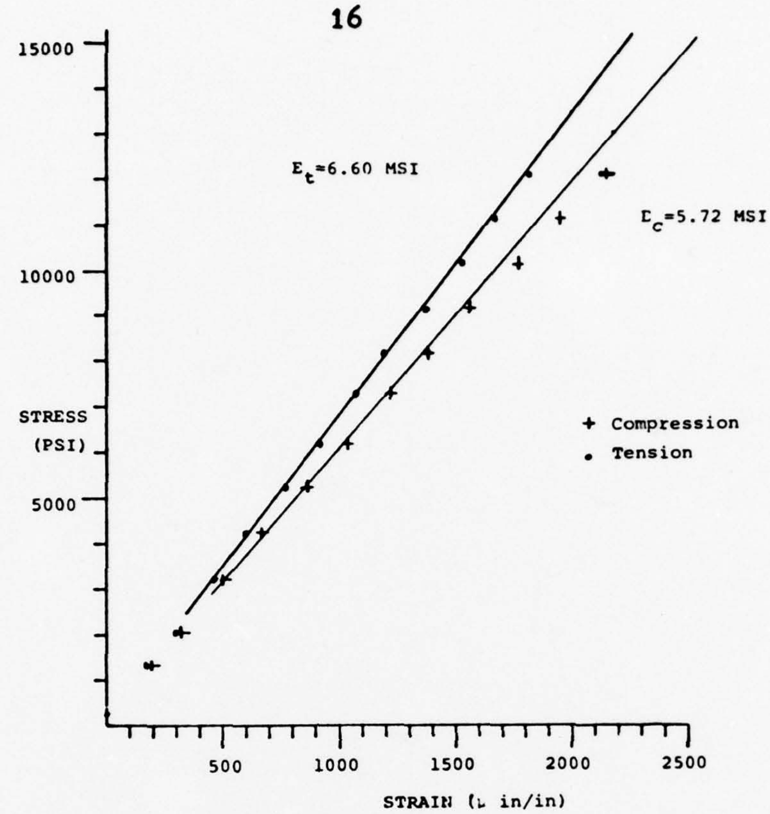
LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	307.	0.	0.
26.	1330.	161.	162.
46.	2352.	296.	276.
66.	3375.	416.	412.
86.	4399.	549.	552.
106.	5421.	699.	696.
126.	6444.	841.	852.
146.	7466.	973.	997.
166.	8489.	1126.	1138.
188.	9510.	1252.	1304.
206.	10535.	1361.	1431.
225.	11506.	1499.	1594.
246.	12580.	1637.	1765.
266.	13603.	1760.	1919.
285.	14575.	1892.	2089.
306.	15649.	2075.	2261.
326.	16671.	2218.	2523.
346.	17694.	******************	******************

MAXIMUM LOAD = 346. POUNDS

MAXIMUM STRESS = 17694. PSI

MAXIMUM N = 234. LB/IN

16



SPECIMEN NUMBER: 1-[illegible] BEAM #2

DATE OF TEST : 15 DEC 75

CORE MATERIAL : CPR URETHANE [illegible]-4

CORE DIMENSIONS: 0.771 X [illegible].65[illegible] X 5.10[illegible] INCHES

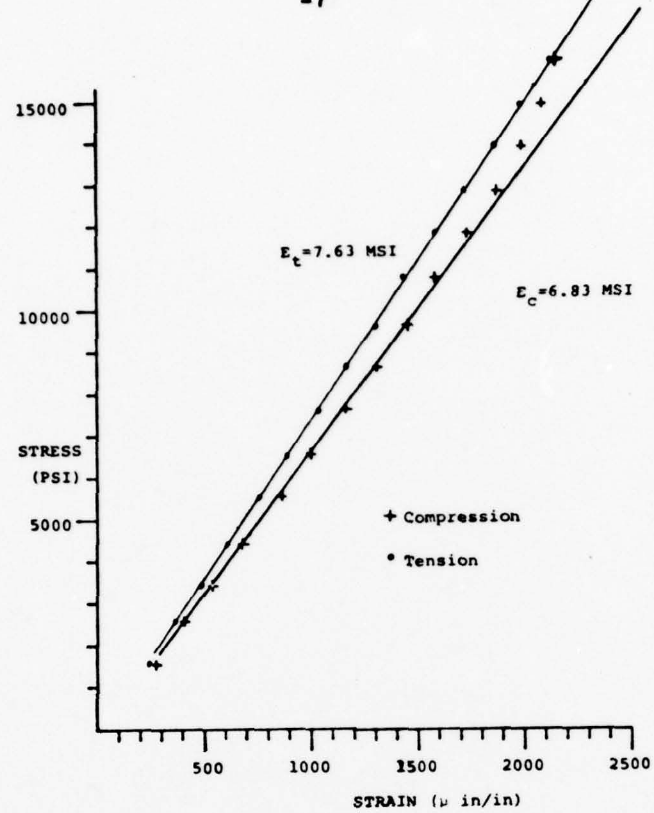
PLY THICKNESS : 0.0135 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	205.	0.	0.
27.	1303.	133.	134.
42.	2065.	302.	315.
66.	3245.	465.	530.
86.	4223.	595.	665.
106.	5212.	766.	863.
126.	6195.	915.	1042.
148.	7277.	1063.	1224.
166.	8162.	1196.	1389.
186.	9145.	1363.	1562.
206.	10128.	1525.	1765.
226.	11112.	1669.	1949.
246.	12095.	1819.	2150.
256.	12587.	************	************

MAXIMUM LOAD = 256. POUNDS

MAXIMUM STRESS = 12587. PSI

MAXIMUM M = [illegible]. IN/IN



SPECIMEN NUMBER: 1-HCOM BEAM #3

DATE OF TEST : 17 DEC 75

CORE MATERIAL : CPR URETHANE 9026-4

CORE DIMENSIONS: 0.765 X 2.620 X 5.100 INCHES

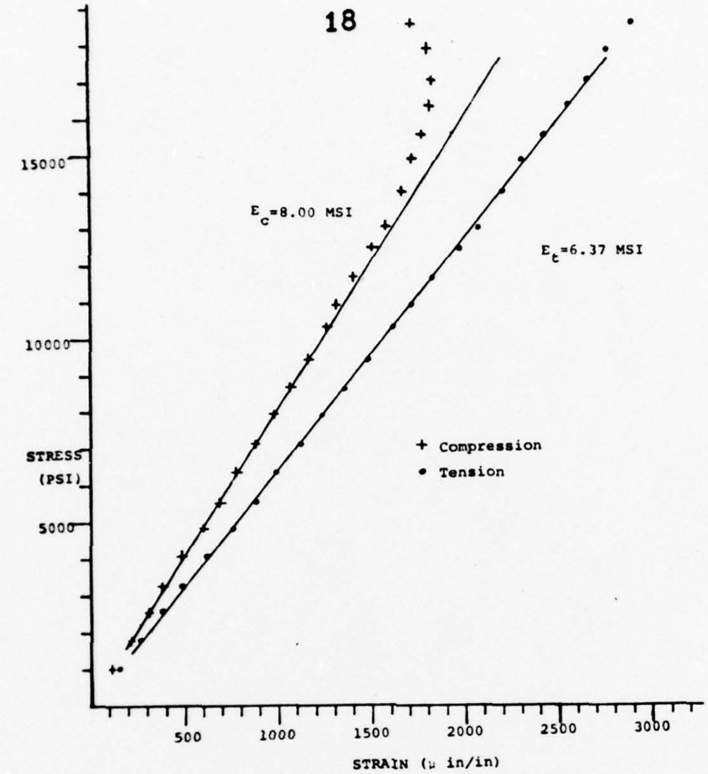
PLY THICKNESS : 0.0120 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	315.	0.	0.
30.	1575.	245.	270.
50.	2598.	371.	409.
66.	3464.	493.	541.
88.	4479.	627.	678.
105.	5563.	769.	863.
125.	6613.	895.	1003.
146.	7563.	1042.	1159.
166.	8712.	1172.	1310.
185.	9720.	1314.	1455.
206.	10912.	1441.	1596.
226.	11961.	1593.	1743.
244.	12836.	1724.	1873.
266.	13961.	1863.	1935.
285.	14958.	1994.	2030.
305.	16008.	2135.	2155.
326.	17110.	********	********

MAXIMUM LOAD = 326. POUNDS

MAXIMUM STRESS = 17110. PSI

MAXIMUM N = 221. LB/IN



SPECIMEN NUMBER: 1-HONEY BEAM #4

DATE OF TEST : 15 DEC 75

CORE MATERIAL : CPR URETHANE 2006-4

CORE DIMENSIONS: 0.772 X 2.650 X 5.100 INCHES

PLY THICKNESS : 0.0172 INCHES

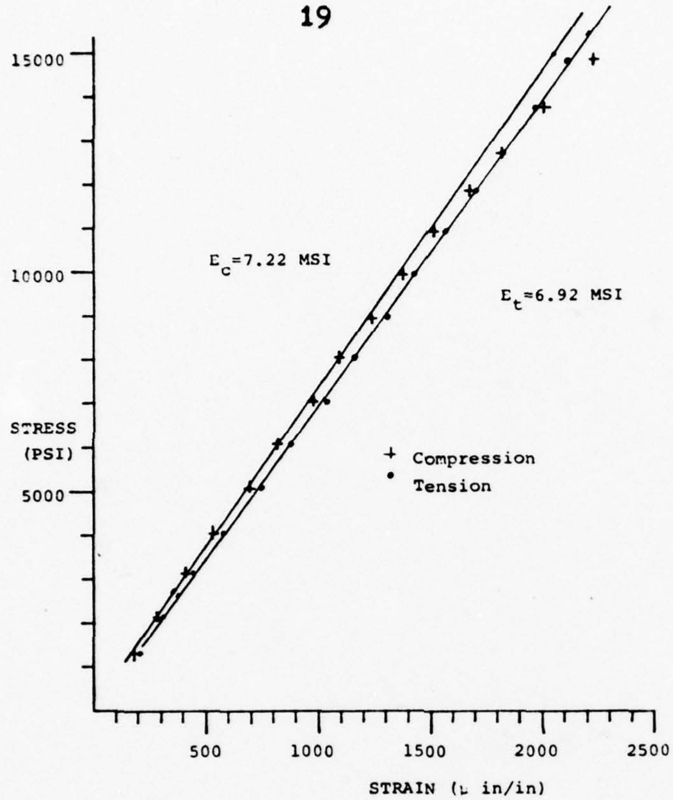
LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	230.	0.	0.
27.	1016.	153.	119.
47.	1833.	272.	216.
69.	2627.	393.	314.
85.	3260.	496.	399.
106.	4066.	635.	496.
126.	4833.	765.	603.
146.	5600.	899.	636.
166.	6367.	999.	789.
186.	7134.	1127.	889.
207.	7901.	1249.	993.
226.	8669.	1364.	1077.
246.	9436.	1493.	1160.
269.	10318.	1629.	1260.
285.	10932.	1723.	1320.
306.	11737.	1841.	1411.
326.	12505.	1979.	1513.
346.	13272.	2085.	1593.
367.	14077.	2213.	1676.
386.	14806.	2319.	1729.
405.	15573.	2433.	1793.
426.	16340.	2556.	1829.
446.	17107.	2667.	1847.
456.	17475.	2776.	1910.
486.	18642.	2877.	1772.
506.	19409.		

MAXIMUM LOAD = 506. POUNDS

MAXIMUM STRESS = 19409. PSI

MAXIMUM N = 330. IN/IN

19



SPECIMEN NUMBER: 1-HOOP BEAM #5

DATE OF TEST : 15 DEC 75

CORE MATERIAL : [illegible] URETHANE [illegible]

CORE DIMENSIONS: 0.766 X 2.500 X 5.100 INCHES

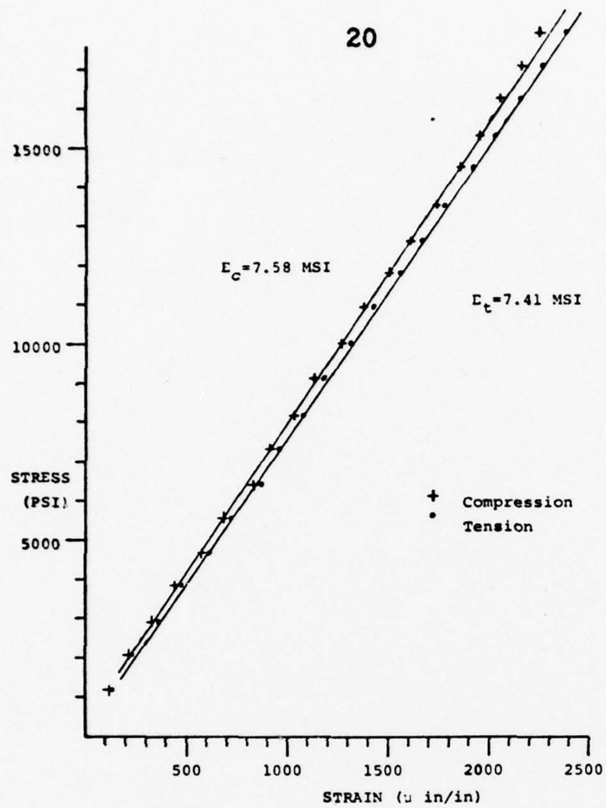
PLY THICKNESS : 0.0142 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	239.	0.	0.
27.	1238.	205.	199.
46.	2212.	311.	297.
66.	3174.	448.	417.
84.	4039.	592.	533.
106.	5037.	755.	[illegible]
126.	6059.	886.	821.
146.	7021.	1043.	991.
167.	8031.	1167.	1101.
186.	8944.	1311.	1245.
206.	9936.	1439.	1381.
226.	10868.	1567.	1526.
246.	11830.	1727.	1692.
265.	12743.	1842.	1846.
286.	13753.	1971.	2006.
307.	14763.	2135.	2236.
326.	15677.		

MAXIMUM LOAD = 326. POUNDS

MAXIMUM STRESS = 15677. PSI

MAXIMUM M = 233. LB/IN



SPECIMEN NUMBER: 1-HCCN BEAM #6

DATE OF TEST : 17 DEC 75

CORE MATERIAL : C?? URETHANE 9?06-4

CORE DIMENSIONS: ?.779 X 2.650 X 5.100 INCHES

PLY THICKNESS : 0.0148 INCHES

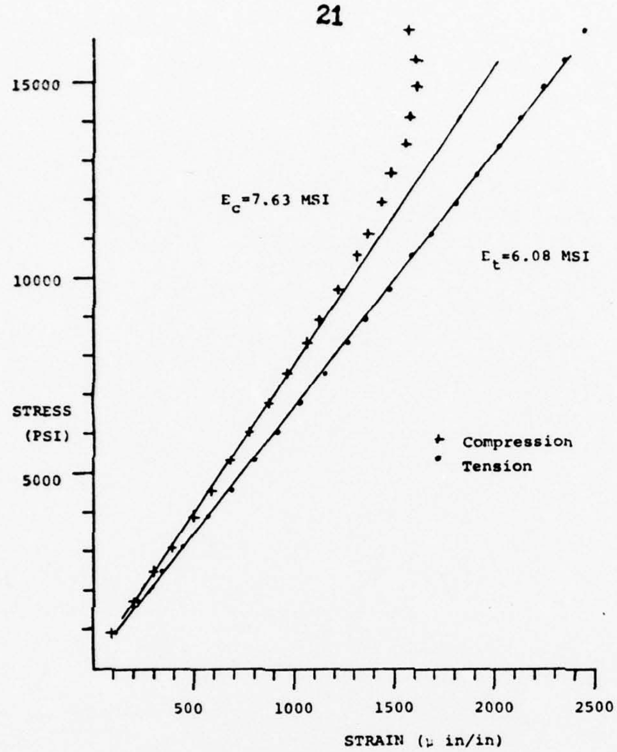
LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	266.	0.	0.
28.	1241.	141.	132.
47.	2093.	283.	274.
66.	2925.	362.	339.
86.	3812.	478.	447.
106.	4639.	609.	575.
126.	5595.	723.	685.
146.	6471.	879.	807.
166.	7357.	959.	917.
185.	8199.	1091.	1032.
206.	9130.	1171.	1146.
226.	10017.	1313.	1260.
247.	10947.	1447.	1392.
266.	11740.	1559.	1504.
286.	12670.	1672.	1611.
305.	13519.	1788.	1724.
327.	14433.	1926.	1851.
346.	15335.	2047.	1950.
367.	16266.	2163.	2068.
386.	17129.	2277.	2165.
406.	17995.	2372.	2252.
426.	18881.	......	......

MAXIMUM LOAD = 426. POUNDS

MAXIMUM STRESS = 18881. PSI

MAXIMUM E = 270. IN/IN

21



SPECIMEN NUMBER: 1-4CON BEAM #7

DATE OF TEST : 16 DEC 75

CORE MATERIAL : CPR URETHANE 9006-4

CORE DIMENSIONS: 0.781 X 2.690 X 5.100 INCHES

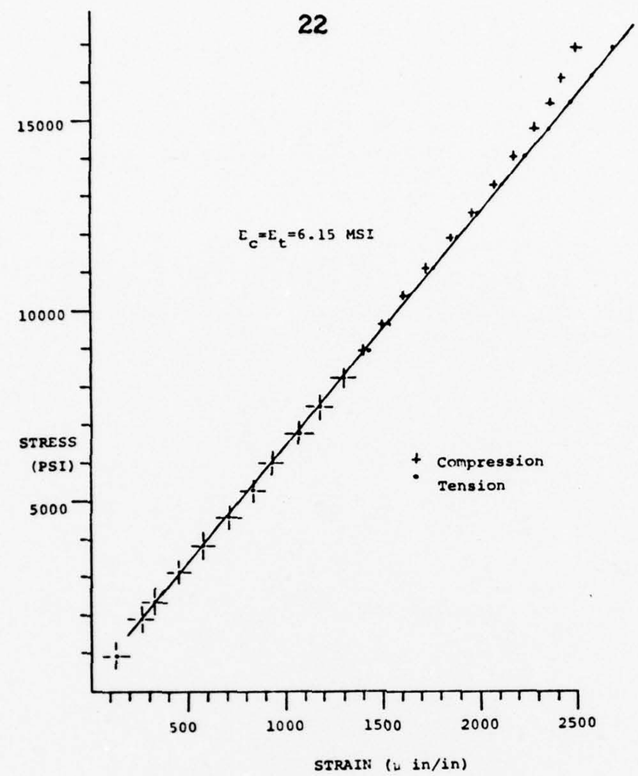
PLY THICKNESS : 0.0176 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	219.	0.	0.
26.	949.	111.	95.
43.	1752.	225.	[illegible]
69.	2519.	347.	302.
97.	3175.	450.	396.
106.	3869.	573.	500.
126.	4503.	693.	595.
145.	5229.	804.	683.
166.	6059.	915.	785.
186.	6793.	1025.	875.
206.	7511.	1154.	967.
229.	8321.	1263.	1062.
244.	[illegible]	1359.	1136.
265.	9707.	1482.	1220.
288.	10510.	1535.	1311.
306.	11167.	1693.	1362.
325.	11837.	1817.	1443.
346.	12627.	1922.	1497.
367.	13323.	[illegible]	1559.
386.	14037.	2143.	1549.
407.	14853.	[illegible]	1615.
425.	15546.	2351.	1623.
447.	16113.	2456.	1590.
456.	16641.	....	....

MAXIMUM LOAD = 456. POUNDS

MAXIMUM STRESS = 16641. PSI

MAXIMUM M = 333. LB/IN



SPECIMEN NUMBER: 1-HCCN BEAM #8

DATE OF TEST : 16 DEC 75

CORE MATERIAL : CPR URETHANE 9006-4

CORE DIMENSIONS: 0.764 X 2.620 X 5.100 INCHES

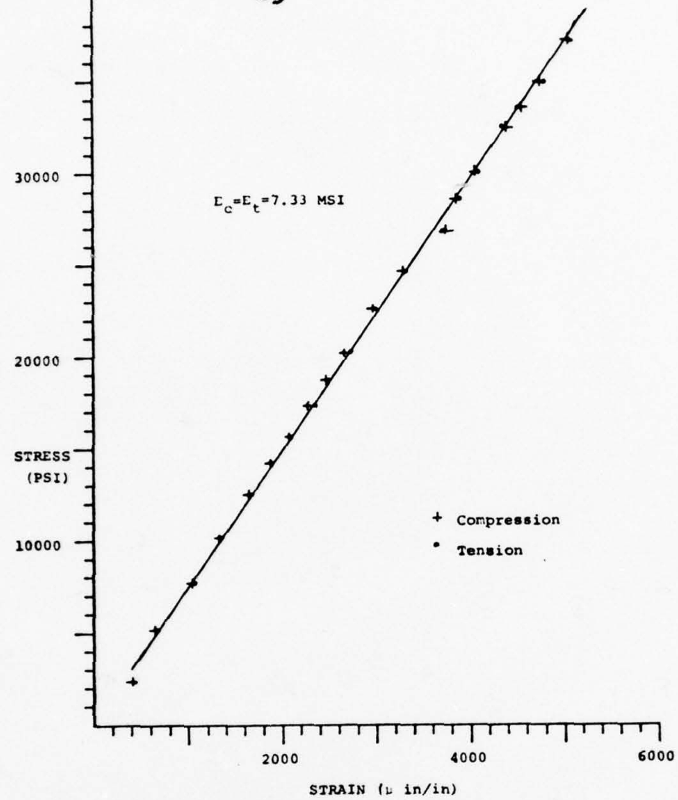
PLY THICKNESS : 0.0185 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN TENSION (U-IN/IN)	STRAIN COMPRESSION (U-IN/IN)
6.	218.	0.	0.
26.	946.	145.	145.
52.	1929.	267.	272.
64.	2328.	338.	338.
86.	3129.	455.	459.
104.	3793.	583.	595.
126.	4584.	710.	728.
145.	5275.	841.	836.
165.	6002.	943.	939.
186.	6766.	1075.	1071.
206.	7443.	1182.	1192.
226.	8222.	1301.	1321.
245.	8942.	1437.	1405.
266.	9677.	1532.	[illegible]
296.	[illegible]	1642.	1668.
306.	11132.	1764.	1722.
327.	11878.	1812.	1858.
345.	12551.	1996.	1952.
366.	13315.	2122.	2072.
386.	14042.	2205.	2175.
406.	14770.	2354.	2270.
426.	15497.	2471.	2364.
446.	16225.	2581.	2432.
466.	16952.	2694.	2498.
486.	17680.	******	******

MAXIMUM LOAD = 486. POUNDS

MAXIMUM STRESS = 17680. PSI

MAXIMUM M = 177. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM #9

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.721 X 2.470 X 5.000 INCHES

PLY THICKNESS : 0.0153 INCHES

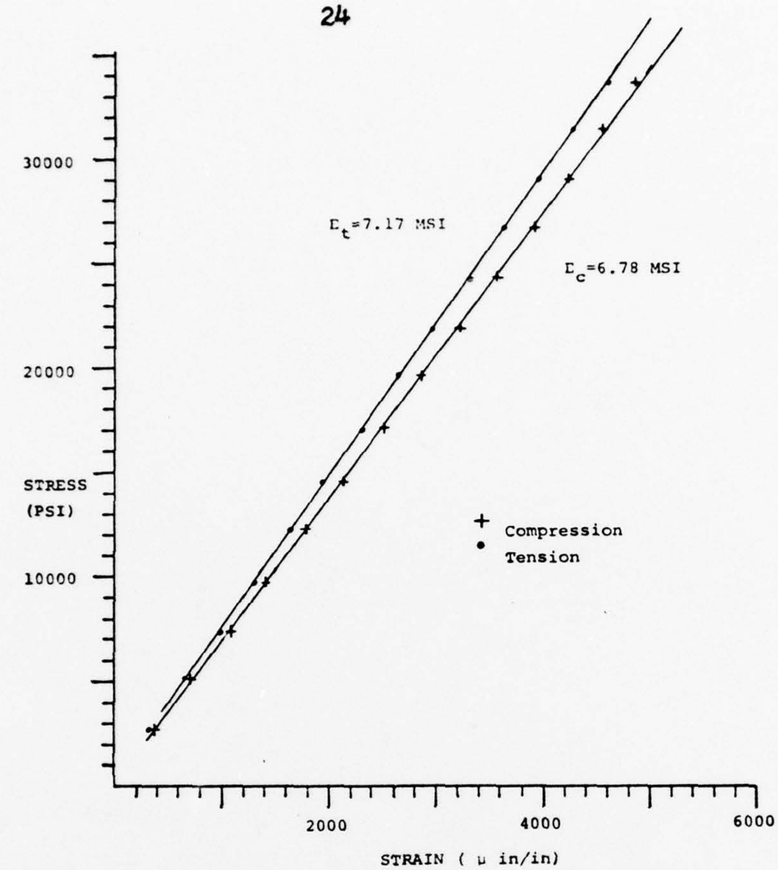
LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	298.	0.	0.
50.	2479.	410.	410.
106.	5256.	660.	690.
156.	7736.	1050.	1070.
206.	10215.	1330.	1350.
254.	12595.	1640.	1660.
288.	14281.	1890.	1900.
316.	15670.	2080.	2090.
351.	17405.	2280.	2380.
378.	18744.	2490.	2500.
408.	20232.	2660.	2750.
456.	22612.	2980.	2980.
497.	24645.	3300.	3340.
541.	26827.	3760.	3740.
577.	28612.	3880.	3890.
607.	30100.	4070.	4070.
657.	32579.	4400.	4360.
678.	33620.	4560.	4530.
706.	35009.	4730.	4760.
753.	37340.	5090.	5110.
805.	39918.	5430.	5430.
828.	41059.	5610.	5620.
846.	41951.	******	******

MAXIMUM LOAD = 846. POUNDS

MAXIMUM STRESS = 41951. PSI

MAXIMUM % = 642. U3/IN

24



SPECIMEN NUMBER: I-HOON BEAM #1C

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.693 X 2.660 X 5.000 INCHES

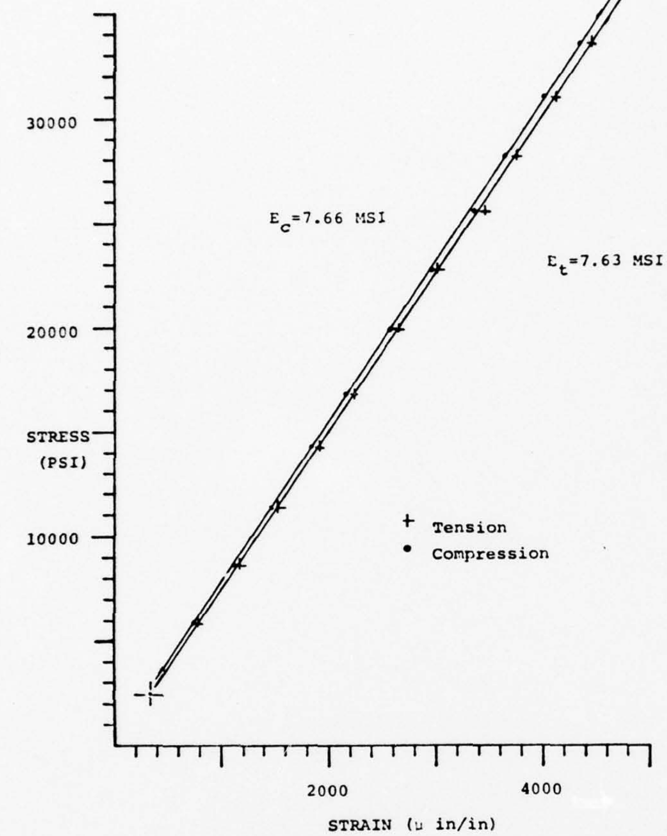
PLY THICKNESS : 0.0153 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	287.	0.	0.
58.	2776.	380.	340.
106.	5074.	730.	670.
156.	7467.	1100.	1000.
204.	9765.	1420.	1310.
258.	12349.	1800.	1640.
305.	14599.	2150.	1970.
357.	17089.	2510.	2310.
408.	19529.	2880.	2660.
458.	21922.	3240.	2990.
508.	24316.	3590.	3330.
558.	26709.	3910.	3640.
606.	29006.	4250.	3980.
658.	31495.	4530.	4300.
704.	33697.	4930.	4620.
756.	36186. ******************************		

MAXIMUM LOAD = 756. POUNDS

MAXIMUM STRESS = 36186. PSI

MAXIMUM [illegible] = 554. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM #11

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.632 X 2.490 X 5.000 INCHES

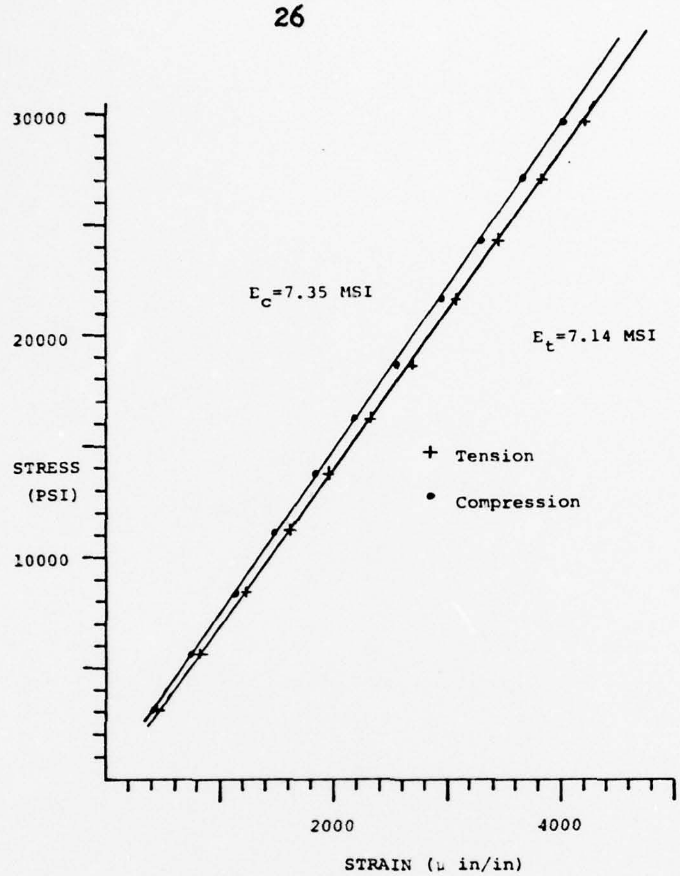
PLY THICKNESS : 0.0143 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	334.	0.	0.
45.	2504.	350.	350.
106.	5899.	760.	790.
156.	8682.	1120.	1190.
206.	11464.	1480.	1540.
258.	14358.	1830.	1930.
304.	16918.	2180.	2260.
359.	19979.	2540.	2670.
409.	22762.	2950.	3030.
459.	25545.	3370.	3450.
508.	28272.	3670.	3780.
557.	30999.	4020.	4150.
607.	33781.	4370.	4490.
637.	35451.******************************		

MAXIMUM LOAD = 637. POUNDS

MAXIMUM STRESS = 35451. PSI

MAXIMUM N = 537. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM #12

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.730 X 2.400 X 5.000 INCHES

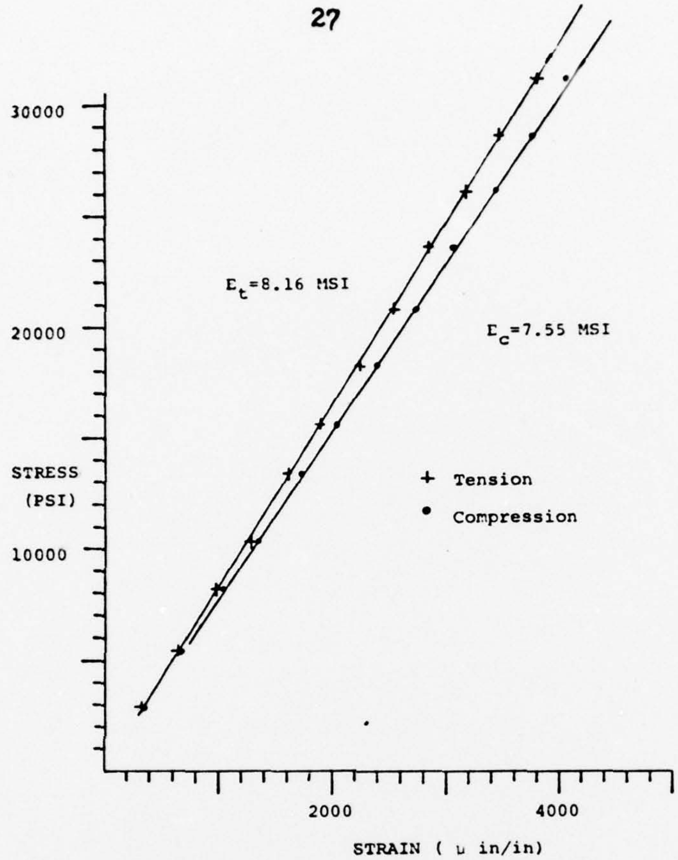
PLY THICKNESS : 0.0145 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	320.	0.	0.
58.	3089.	410.	450.
106.	5645.	760.	830.
158.	8415.	1140.	1230.
209.	11131.	1490.	1610.
258.	13740.	1840.	1980.
306.	16297.	2190.	2340.
354.	18853.	2560.	2700.
407.	21676.	2940.	3090.
457.	24339.	3300.	3460.
509.	27055.	3670.	3850.
557.	29664.	4020.	4210.
591.	31475.	******************	******************

MAXIMUM LOAD = 591. POUNDS

MAXIMUM STRESS = 31475. PSI

MAXIMUM N = 456. LB/IN



SPECIMEN NUMBER: 1-HOOP BEAM # 13

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.692 X 2.650 X 5.000 INCHES

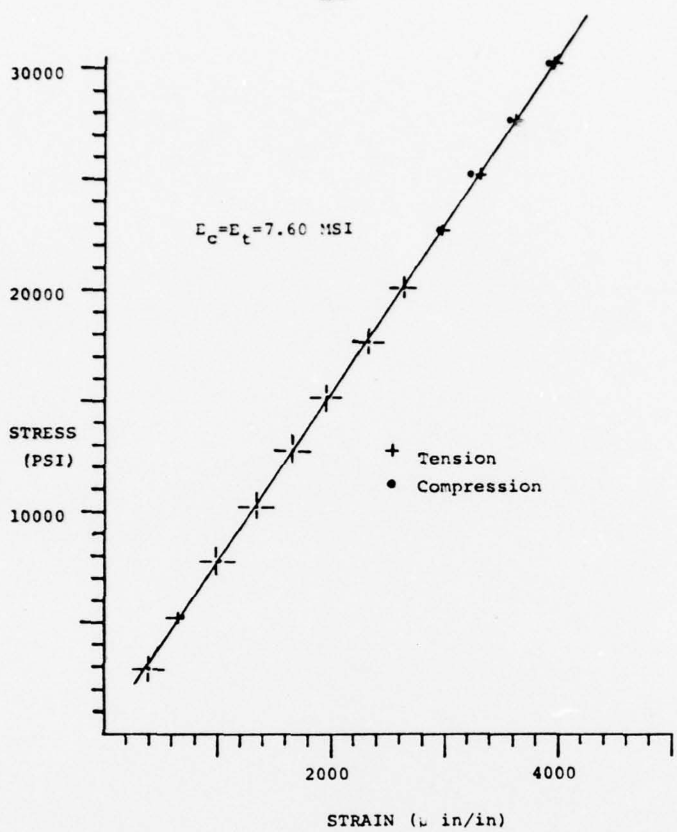
PLY THICKNESS : 0.0143 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	309.	0.	0.
58.	2990.	360.	340.
106.	5465.	690.	650.
160.	8248.	1040.	990.
208.	10723.	1370.	1290.
261.	13455.	1720.	1610.
305.	15723.	2040.	1900.
356.	18353.	2400.	2240.
404.	20827.	2720.	2540.
457.	23559.	3070.	2860.
508.	26199.	3430.	3190.
557.	28715.	3780.	3490.
608.	31344.	4070.	3800.
636.	32747.******************************		

MAXIMUM LOAD = 636. POUNDS

MAXIMUM STRESS = 32747. PSI

MAXIMUM W = 464. LB/IN



SPECIMEN NUMBER: I-HOON BEAM # 14

DATE OF TEST : 5 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.715 X 2.650 X 5.000 INCHES

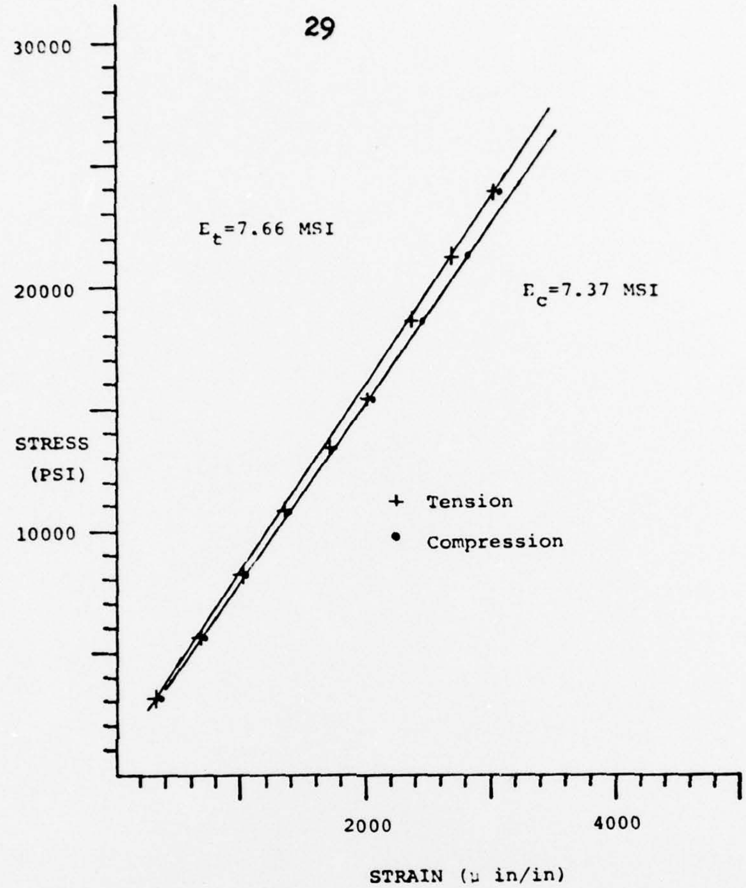
PLY THICKNESS : 0.0144 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	297.	0.	0.
60.	2974.	400.	400.
106.	5255.	700.	690.
157.	7783.	1040.	1030.
206.	10212.	1350.	1350.
258.	12740.	1640.	1630.
304.	15070.	1960.	1980.
357.	17698.	2330.	2330.
406.	20127.	2640.	2640.
456.	22606.	2950.	2960.
508.	25163.	3280.	3310.
558.	27662.	3590.	3620.
610.	30240.	3910.	3940.
646.	32025.	**************	**************

MAXIMUM LOAD = 646. POUNDS

MAXIMUM STRESS = 32025. PSI

MAXIMUM N = 461. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM #15

DATE OF TEST : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.710 X 2.640 X 5.000 INCHES

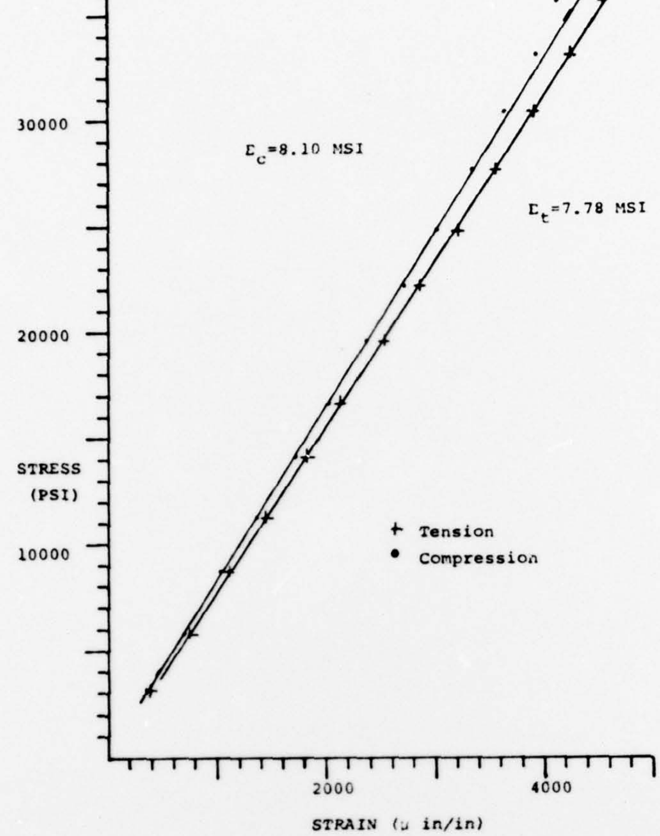
PLY THICKNESS : 0.0138 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	314.	0.	0.
58.	3035.	360.	340.
106.	5547.	710.	700.
157.	8215.	1060.	1050.
207.	10832.	1400.	1360.
257.	13448.	1740.	1700.
305.	15960.	2070.	2010.
357.	18681.	2470.	2380.
408.	21345.	2810.	2700.
457.	23913.	3090.	3040.
507.	26550.**********	******************	**********

MAXIMUM LOAD = 507. POUNDS

MAXIMUM STRESS = 26550. PSI

MAXIMUM N = 366. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM # 1C

DATE OF TEST : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.669 X 2.640 X 5.000 INCHES

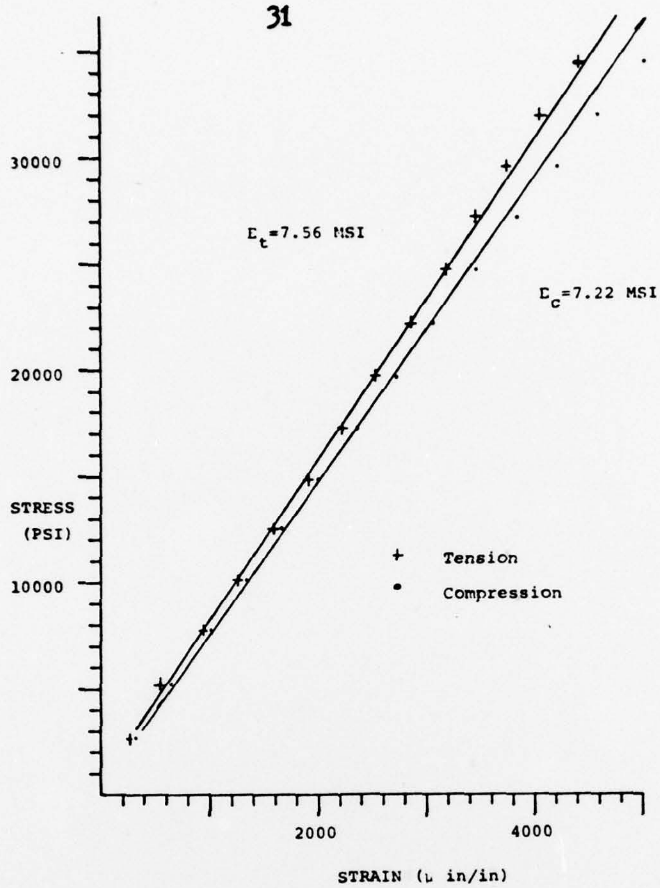
PLY THICKNESS : 0.0140 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	328.	0.	0.
58.	3170.	360.	390.
106.	5794.	700.	750.
160.	8746.	1040.	1110.
207.	11315.	1380.	1460.
258.	14102.	1710.	1820.
304.	16616.	2020.	2150.
358.	19568.	2390.	2550.
409.	22301.	2710.	2890.
456.	24925.	3010.	3220.
507.	27712.	3350.	3590.
558.	30500.	3650.	3940.
608.	33233.	3930.	4290.
654.	35747.	4130.	4590.
676.	36950.********	********	********

MAXIMUM LOAD = 676. POUNDS

MAXIMUM STRESS = 36950. PSI

MAXIMUM N = 517. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM # 17

DATE OF TEST : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.714 X 2.680 X 5.000 INCHES

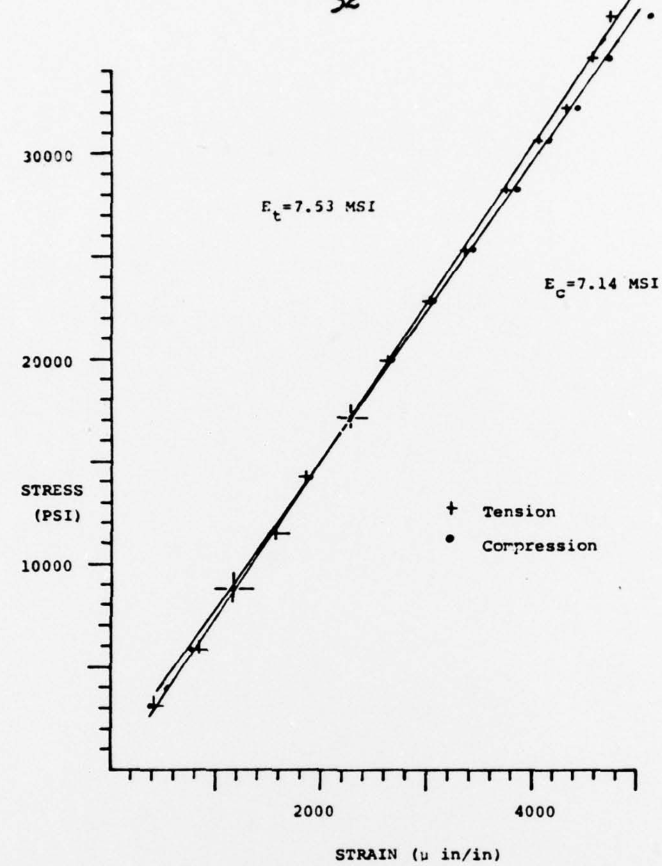
PLY THICKNESS : 0.0145 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	292.	0.	0.
55.	2681.	310.	290.
106.	5166.	660.	650.
158.	7701.	1010.	970.
207.	10089.	1350.	1290.
258.	12575.	1680.	1600.
305.	14866.	2020.	1920.
356.	17352.	2380.	2240.
402.	19594.	2720.	2540.
456.	22226.	3080.	2860.
508.	24760.	3450.	3200.
557.	27146.	3830.	3480.
607.	29585.	4210.	3790.
657.	32025.	4600.	4090.
708.	34508.	5030.	4410.
726.	35386.	**************	**************

MAXIMUM LOAD = 726. POUNDS

MAXIMUM STRESS = 35386. PSI

MAXIMUM K = 513. LB/IN



SPECIMEN NUMBER: 1-HOCN BEAM # 18

DATE OF TEST : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.735 X 2.490 X 5.000 INCHES

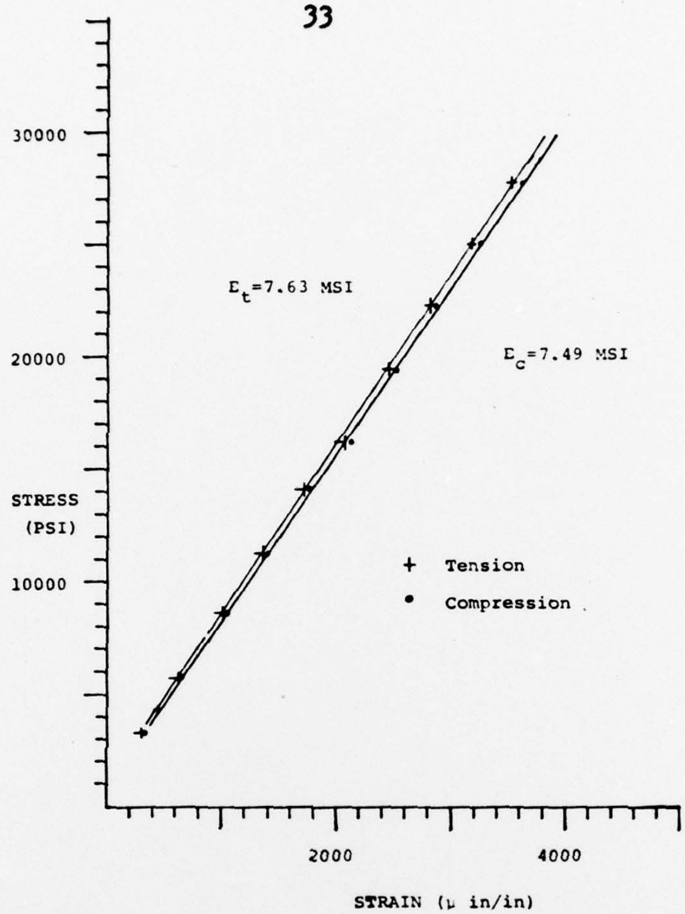
PLY THICKNESS : 0.0138 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	335.	0.	0.
56.	3128.	390.	430.
106.	5922.	760.	840.
159.	8883.	1160.	1180.
207.	11564.	1540.	1570.
256.	14301.	1900.	1380.
307.	17151.	2300.	2300.
356.	19888.	2680.	2650.
409.	22849.	3090.	3050.
454.	25303.	3440.	3380.
506.	28268.	3850.	3780.
548.	30614.	4190.	4080.
579.	32346.	4460.	4340.
620.	34636.	4760.	4600.
656.	36647.	5170.	4770.
662.	36933.******************************		

MAXIMUM LOAD = 662. POUNDS

MAXIMUM STRESS = 36933. PSI

MAXIMUM N = 513. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM # 19

DATE OF TEST : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.704 X 2.570 X 5.000 INCHES

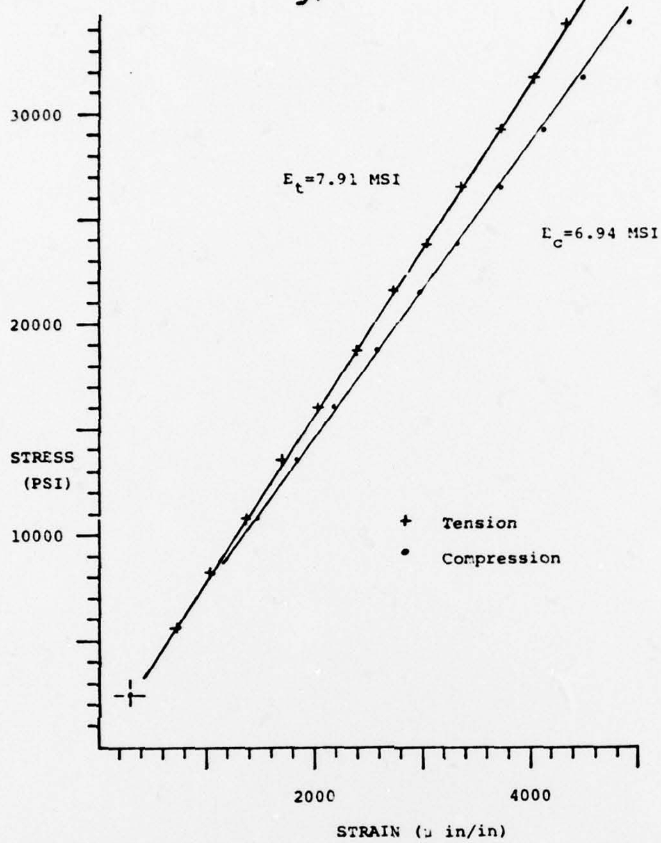
PLY THICKNESS : 0.0136 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	330.	0.	0.
61.	3356.	320.	310.
106.	5831.	680.	650.
157.	8657.	1040.	1030.
207.	11388.	1400.	1370.
256.	14084.	1770.	1730.
304.	16724.	2120.	2060.
354.	19475.	2550.	2450.
407.	22391.	2890.	2820.
456.	25086.	3280.	3190.
506.	27837.	3610.	3510.
560.	30806.	*************************	************

MAXIMUM LOAD = 560. POUNDS

MAXIMUM STRESS = [illegible]. PSI

MAXIMUM N = 419. LB/IN



SPECIMEN NUMBER: 1-HOON BEAM # 2C

DATE OF TEST : 12 FEB 76

CORE MATERIAL : PVC FOAM

CORE DIMENSIONS: 0.705 X 2.570 X 5.000 INCHES

PLY THICKNESS : 0.0142 INCHES

LOAD (POUNDS)	STRESS (PSI)	STRAIN COMPRESSION (U-IN/IN)	STRAIN TENSION (U-IN/IN)
6.	315.	0.	0.
48.	2523.	300.	300.
108.	5678.	760.	710.
157.	8254.	1090.	1040.
208.	10935.	1470.	1370.
258.	13564.	1810.	1700.
305.	16034.	2190.	2030.
355.	18621.	2590.	2430.
410.	21554.	2990.	2740.
456.	23973.	3320.	3040.
506.	26601.	3720.	3380.
559.	29388.	4120.	3720.
606.	31858.	4500.	4030.
656.	34487.	4920.	4350.
696.	36590.	**************	**************

MAXIMUM LOAD = 696. POUNDS

MAXIMUM STRESS = 36590. PSI

MAXIMUM N = 520. LB/IN

APPENDIX A

TABLE A1 FOAM PROPERTIES

FOAM		CPR URETHANE 9006-4	AIREX 01/18 PVC FOAM
COMPRESSIVE STRENGTH (psi)	PARALLEL *	55	120
	PERPENDICULAR	75	
COMPRESSIVE MODULUS OF ELASTICITY (psi)	PARALLEL	900	5000
	PERPENDICULAR	2000	
TENSILE STRENGTH (psi)	PARALLEL	70	260
	PERPENDICULAR	90	
SHEAR STRENGTH (psi)		50	125
NOMINAL DENSITY (lb/ft^3)		4	6

* Indicates a direction of loading parallel to the face of the beam and applies only to the urethane foam.

TABLE A2 GRAPHITE PROPERTIES

MANUFACTURER	Hercules Incorporated
PHYSICAL PROPERTIES*	
Fiber Volume	59%
Density	.0577 lb/in^3
Ply Thickness	.0053 in.
LAMINATE MECHANICAL PROPERTIES*	
0^o Tensile Strength	239 ksi
0^o Tensile Modulus	20.5 msi
0^o Flex Strength	276 ksi
0^o Flex Modulus	17.2 msi
Short Beam Shear Test	18.9 ksi

* Values are for 1-ply laminate cured as recommended by the manufacturer.

Manufacturer's Recommended
Graphite Curing Cycle A01

Laminates shall be cured as follows:

a. Preheat press platens to 275 ± 5°F.

b. Place mold in press and apply contact pressure of 10-15 pounds per square inch (psi).

c. Hold at contact pressure of Step b. for 18 ± 1 minutes.

d. Increase pressure to 100 + 10, − 0 psi.

e. Increase temperature to 300 ± 5°F.

f. Hold at 100 + 10, − 0 psi and 300 ± 5°F for 30 ± 5 minutes.

g. Increase temperature to 350 ± 5°F and hold for 30 ± 5 minutes.

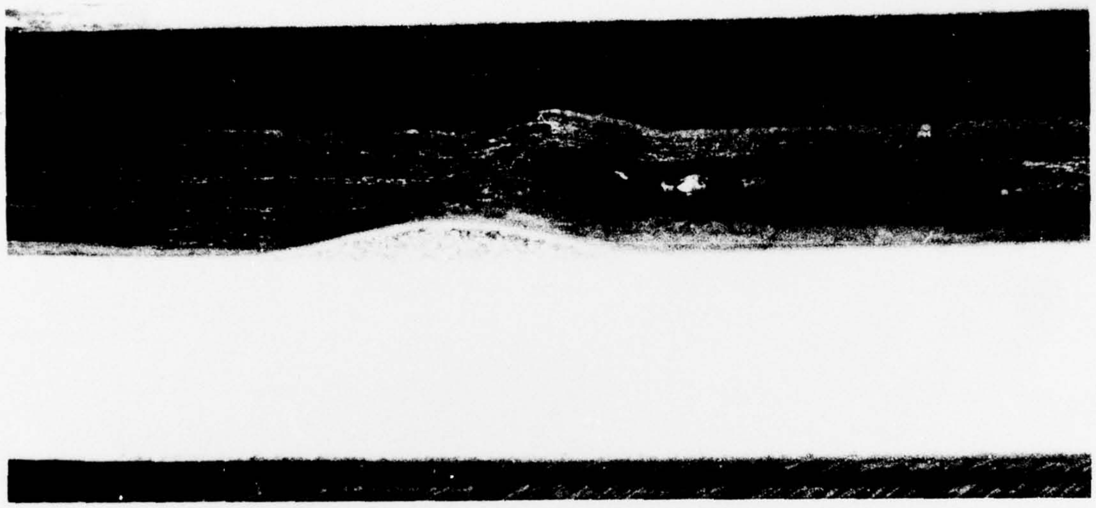
h. Decrease temperature at a rate of 13 ± 2°F per minute until temperature of 150 ± 5°F is reached.

i. Release pressure.

j. Remove mold from press.

k. Remove laminate from mold.

APPENDIX B



Failure Mode "a"

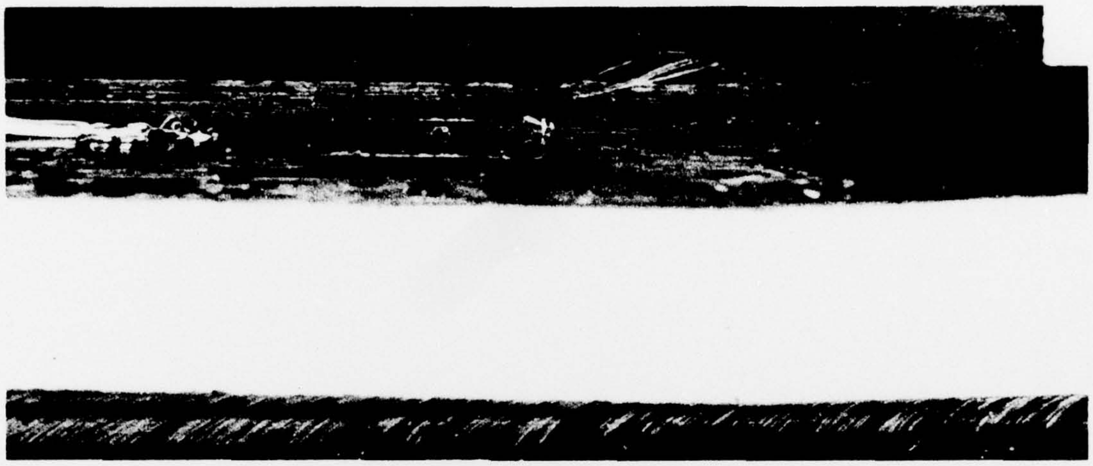
Failure Mode "a" was a tension failure of the foam core which allowed the graphite facing to buckle outward. It was found to occur only with the Urethane foam core beams and was the method of failure in all eight cases. The half-wavelength of the buckling varied from 5/8" to 1-3/8" and often varied from one edge of the beam to the other. Failure was very rapid and was always occumpanied by a "popping" sound as the graphite tore loose. The failures occurred at relatively low levels of stress when compared with the PVC foam core beams.

Failure Mode "b"

Failure Mode "b" was a compression failure of the graphite facing. This failure mode occurred on five of twelve occasions where PVC foam was used as core material. The failure line was characteristically very jagged through the facing with little apparent permanent deformation of the core material. Failures occurred at stress levels of 25,000-35,000 psi. (The compressive ultimate strength of the laminate is about 90,000 psi.)

Failure Mode "c"

Failure Mode "c" appeared to be a combination failure of the PVC foam and the graphite facing although it is probable that one caused the other to occur. The failure of the foam was a compression failure and can be identified on the beam by the straight, sharp V-shaped indentation. It varied in length from about ½" to 1-3/4" with the remainder of the facing failing in compression similarly to Mode "b". This mode of failure occurred on six of twelve occasions with the PVC foam core beams.



Failure Mode "d"

Failure Mode "d" was one-of-a-kind and occurred only on beam #17. It is very similar to Mode "b" except that some interlaminar delamination occurred on one edge of the beam sufficient to weaken the beam locally and allow compressive failure of the graphite facing to occur at that site. Although delamination was about $\frac{1}{4}$" wide, it is interesting to note that the maximum compressive load, N_{max}, was comparable to that of all other failures.