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INVESTIGATION OF LOW VELOCITY IMPACT DAMAGE ON FILAMENTARY COMPOSITE MATERIALS

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ABSTRACT

This report presents the results of an experimental investigation of the affect of low velocity impact on the residual modulus and residual strength of flat filamentary composite materials. Theoretical analysis of composite materials indicates that the modulus of the material must decrease as impact damage increases. This dectease must also correlate to the decrease in residual strength. This study is an initial investigation to verify these hypotheses.

Graphite/epoxy laminates (AS4/3501-6) of various fiber orientations (8[0°], 2[±45°]$_8$) were impacted using a falling weight impact tester. Impact energies ranged from 0.42 to 1.55 ft.-lb., with impact velocities from 2.03 to 3.98 ft./sec. The results show that there is a reduction in residual modulus of the plate as the impact energy increases.

ACKNOWLEDGEMENTS

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My special thanks goes to Mr. Frank Ledbetter for his assistance in the conduct of this research. He contributed many ideas which were essential to the success of this project. I greatly appreciate the time he took from his work to assist me throughout the summer.

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INTRODUCTION

The concept of a reinforcing materials with filaments dates back to the time of the Egyptian empire. However, the application of this concept has been, until the twentith century, limited in practice. Developments in chemistry and manufacturing techniques have resulted in the recent growth of the use of filamentary composite materials. As with many of man's developments, the ability to produce a structure from filamentary composite materials has exceeded the understanding and/or the ability to analyize.

The use of filamentary composite materials has grown rapidly since the 1940's. The principal material being glass fibers suspended in an epoxy matrix. The early applications of the material were to non-structural components where the analysis of the additional stiffness provided was not necessary and where damage to the material did not reduce the strength of the structure. The use of fiber glass/epoxy in structural applications has increased as the confidence in the material has grown. Typically, in the early stages of use, analyses performed on these structures involved application of principals derived from the behavior of metals. With the appropriate application of engineering judgement, the structures produced proved to be safe. Today, more advanced fibers are available for use. These new fibers have been developed for application as primary structural members which are ligher than comparable metalic members. As the use of composite materials in critical areas increases it becomes ever more important that the behavior of these materials be thoroughly understood.

One area in which the behavior of filamentary composite materials is only beginning to be understood is in response to damage. Experience with metals has demonstrated that as the level of damage increases in a structure, there is a reduction in the remaining strength of the structure. The damage may be due to either impact loads or fatigue. Composite materials have been shown to have the same basic behavior [1-2]. Composite materials of glass and graphite are more sensitive to impact damage than metals, due to the brittle nature of the fibers. Metals to not demonstrate a reduction in stiffness as the level of damage increases. It is only recently that it has been postulated, and shown, that filamentary composites have a reduction in stiffness as the level of fatigue increases [3]. It is then proposed that the stiffness of the composite should decrease as the level of impact damage increases. If the modulus of the material is dependent on the damage level, this will adversely affect any analysis of the structure. A positive aspect of this behavior may be that for a specific level of damage, it should be possible to correlate the residual strength with the residual modulus. This then provides a mechanism for easily measuring the residual strength of the structure by non-destructive methods.

The following section presents a statement of the objectives of this research. The third section is a discussion of the rule of mixtures as it applies to the analysis of damaged filamentary composites. The test program is discussed in the section on methodology. The results from the tests performed on the graphite/epoxy panels is presented in the fifth section. Finally, the last section of the report contains the conclusions and recommendations.

OBJECTIVES

The objective of this research is to determine if the modulus of a filamentary composite material is dependent on the level of impact damage.

The initial investigation will attempt to determine the affect of low velocity impact on the residual modulus of graphite/epoxy composite panels. If the residual modulus does depend on the impact damage an attempt will be made to correlate the residual strength with the residual modulus.

THEORY

The rule of mixtures has been proven to be an upper bound on the modulus for a lamina [1]. The rule of mixtures is:

$$E_1 = E_f v_f + E_m v_m$$

where E_1 is the modulus of elasticity of the lamina in the principal material direction, E_f and E_m are the moduli of the fiber and matrix respectively, and v_f and v_m are the volume fractions of the fiber and matrix respectively. In the undamaged state

$$v_m = 1 - v_f \ .$$

Thus, to determine the modulus of the lamina it is only necessary to know the volume fraction of the fiber or matrix and the moduli of the fiber and matrix. However, if the lamina is damaged the rule of mixtures can only provide an upper bound to the lamina moduli.

The rule of mixtures as adapted to include damage is

$$E_1 = E_f f(v_f, v_d) + E_m v_m$$

where f is a function of the total volume fraction of fibers and the volume fraction of damaged fibers, v_d. The form of f is such that

$$f(v_f, 0) = v_f \quad \text{and} \quad f(v_f, v_f) \geq 0.$$

The first restriction provides that in the undamaged state the origional form of the rule of mixtures applies. The second provides that there is a contribution to the stiffness in the principal direction, even if all the fibers are broken (resulting in a directional particulate composite). To fully develop f it will be necessary to analyze the load transfer from one fiber to another around the region of damaged, e.g. broken fibers. It has been shown that there is a characteristic length associated with the load transfer between fibers. This length then will contribute to the volume fraction of the damaged fiber. Development of f from a theoretical analysis is left for future study.

METHODOLOGY

MATERIAL PREPARATION

The material used for this project is Hercules AS4/3501-6 graphite/epoxy. The test panels used were made from prepreg stock according the to cure cycle indicated. Three unidirectional panels, 12 inches by 12 inches, with eight ply were laidup for the tests. Eight ply was selected based on the ASTM guidelines for determining the principal material direction properties. An additional set of four laminate panels were laidup with an orientation of $2[\pm45°]_s$. This configuration was selected to investigate the effect of laminate orientation on the level of damage developed.

The unidirectional panels were cut up into ten specimens, ten inches by one inch, after the ASTM method. The four ±45° panels were cut into seven specimens, eight inches by one inch.

IMPACT TESTING

An MTS falling weight impact test machine was modified for use in these tests. The falling weight impact test machine used a General Research Corporation data aquisition system. The impact tup of the GRC system had a weight of approximately four pounds. Combined with the carriage the total impactor weight was 8.9 lbs. This was determined to be to large for practical use. After modification the total weight is 6.49 lbs. This is still a large value, however, time did no permit further modifications to reduce the total weight. This introduces a limit to the velocity of impact.

The anvil of the impact tester has a 0.52 inch hole for the tup to pass through. This diameter was selected to provide support to the edges of the one inch wide test specimens. To minimize the cutting of fibers a nylon plate of .15 inches in thickness was used as a support for the specimens. The penetrator hole in the nylon back plate has an outside diameter of 0.53 inches on the specimen side and an interior diameter of 0.52 inches on the anvil side. This is also acts to reduce fiber cutting.

For the unidirectional panels nine samples were tested at drop heights ranging from one inch to three inches. The tenth sample was not impacted to provide an undamaged sample for comparison. The maximum drop height was determined such that there were no fibers cut in an impact. All samples were impacted at their mid points.

The $\pm 45^\circ$ laminates were tested in the same maner as the unidirectional panels. Six of the seven samples were impacted from drop heights from one inch to 2.25 inches.

TENSILE TESTING

The tensile tests were performed using an INSTRON universal test machine. Due to equipment problems it was necessary to measure the specimen elongation by the cross-head deflection. This is a method which is less than desirable and which had a strong adverse impact on the results obtained.

After the samples had been impacted they were prepared for the tensile tests by attaching clamping pads. These pads were attached by adhesives to minimize the fiber breakage due to the jaws of the grips.

The ultimate load for each specimen was obtained directly from the tensile test. The modulus of each sample is a tangent modulus obtained from the cross-head position and load data.

RESULTS

The results obtained from the tests performed are shown in Figures VI-1 through VI-6 and Tables VI-1 and VI-2. Figures VI-1 and VI-2 are plots from the impact tests, while the remaining plots are from the tensile tests.

IMPACT RESULTS

In all of the samples tested the location of the impact site is clearly observable by the naked eye. In the unidirectional samples at higher impact energies the fibers on the side of the sample opposite the impacter were broken along lines perpendicular to the fibers. In addition, some of the samples were clearly fractured lengthwise by the impact.

Figure IV-1 is a plot of the impact load verse time and impact energy verse time for a unidirectional sample at a drop height of 2.5 inches. The load trace is characteristic of the impact of fiber reinforced materials. At a load of approximately 30 lbs the curve has a discontinuity which indicates a fiber or fibers breaking. Again at a load of approximately 190 lbs. there is a sharp drop in load which indicates breaking several fibers. The maximum load is achieved, just prior to more fibers breaking. The oscilations in the load curve at times greater than 10 msec are not related to physical processes occuring in the sample. Rather, they relate to the response of the tup on rebound after impact.

Figure IV-2 is a plot of the impact load verse time and impact energy verse time for a ±45° laminate sampled at a drop height of 1.25 inches. Much less fiber breakage is observed in this plot than in that for the unidirectional sample. The changes at approximately 90 lbs. and at approximately 180 lbs. indicate fibers breaking. The loads at which fibers broke do not appear to have any pattern, occuring in a seemingly random pattern.

The energies and velocities of the impacts are listed in Tables VI-1 and VI-2. For the method used to release the carriage the comparitively small standard deviation in the energies is quite surprising.

TENSILE RESULTS

Figures IV-3 and IV-4 show results from the tensile tests of the unidirectional samples. Figure IV-3 is a plot of the average ultimate stress verse the impact energy. The bars indicate one standard deviation above and one standard deviation below the average value. A least squares interpolation of the points yields

$$X(\psi) = -42170\,\psi + 171000$$

where ψ is the impact energy, and X is the ultimate stress. The confidence level for the least squares approximation is 0.49 (1.0 indicating a perfect fit). This indicates that a linear least squares approximation does not fit the data well.

The handbook value for ultimate strength is 312.7 kpsi. The ultimate stress obtained in these tests for the undamaged state do not compare to this value. This is probably due to difficulties encountered in clamping the samples without breaking the fibers.

Figure IV-4 is a plot of the modulus of the unidirectional samples verses the impact energy. As in the ultimate stress plot, the bars indicate one standard deviation above and one standard deviation below the plotted average. The plot indicates that there is a reduction in the modulus as impact energy increases. A linear least squares approximation yields

$$E_1(\psi) = -1112000\,\psi + 5165000$$

The confidence level for the approximation is 0.53.

The unidirectional modulus obtained in the undamaged state does not compare to the handbook values for this material (E_1 = 20.7 Mpsi). One undamaged specimen was tested using a strain indicator. The results of that test produced E_1 = 20.0 Mpsi. Since the values are consistent, the conclusion is that the error is systematic, resulting from measuring the elongation by cross-head deflection. This then requires that the data be compared only among these tests or tests performed using the same methods.

The results for the unidirectional samples are listed in Table IV-1.

One important observation of the failure mode for the unidirectional samples is made. In the samples with discernable breaks in the fibers the flaws did not propagate in the plane of the flaw. Rather, the flaw propagated in the direction of the fibers. The result, a rectangular opening at the site of impact. This observation supports the conclusions reached in [4].

Figure IV-5 is a plot of the average ultimate stress for the ±45° laminates verses impact energy. The bars denote the plus one and minus one standard deviation band. There is considerable scatter in the data. Table IV-2 is a list of the results for the ±45° laminates. Examining the data it is clear that panel 2 is of higher quality than the other panels. This contributes to the scatter.

A linear least squares approximation of the data in the figure yields

$$X(\psi) = -1450\psi + 18740$$

with a confidence of 0.82.

A plot of the modulus verses the impact energy is shown in Figure IV-6. As with the unidirectional tests the modulus measured does not compare to the expected value ($E = 3.63$ Mpsi). This supports the conclusion that the fault lies in the method of deflection measurement. The plot shows that, again, the modulus decreases as the impact energy increases. Applying a power form of the least squares approximations produces

$$E_1(\psi) = 606400\,\psi^{-0.08}\ .$$

The confidence level is 0.80. The negative exponent demonstrates the inverse relation between modulus and impact engergy.

CONCLUSIONS AND RECOMMENDATIONS

The results from this investigation show that the modulus of a filamentary composite material decreases as the level of impact energy and hence damage increases.

Insufficient data was obtained to determine if a relationship exists between the residual modulus and residual strength.

This is only a preliminary study. Due to equipment problems this data is at best self consistent. Nevertheless, these results call for further investigation. In these investigations larger sample sets should be used and the modulus measurements should be performed using an extenseometer.

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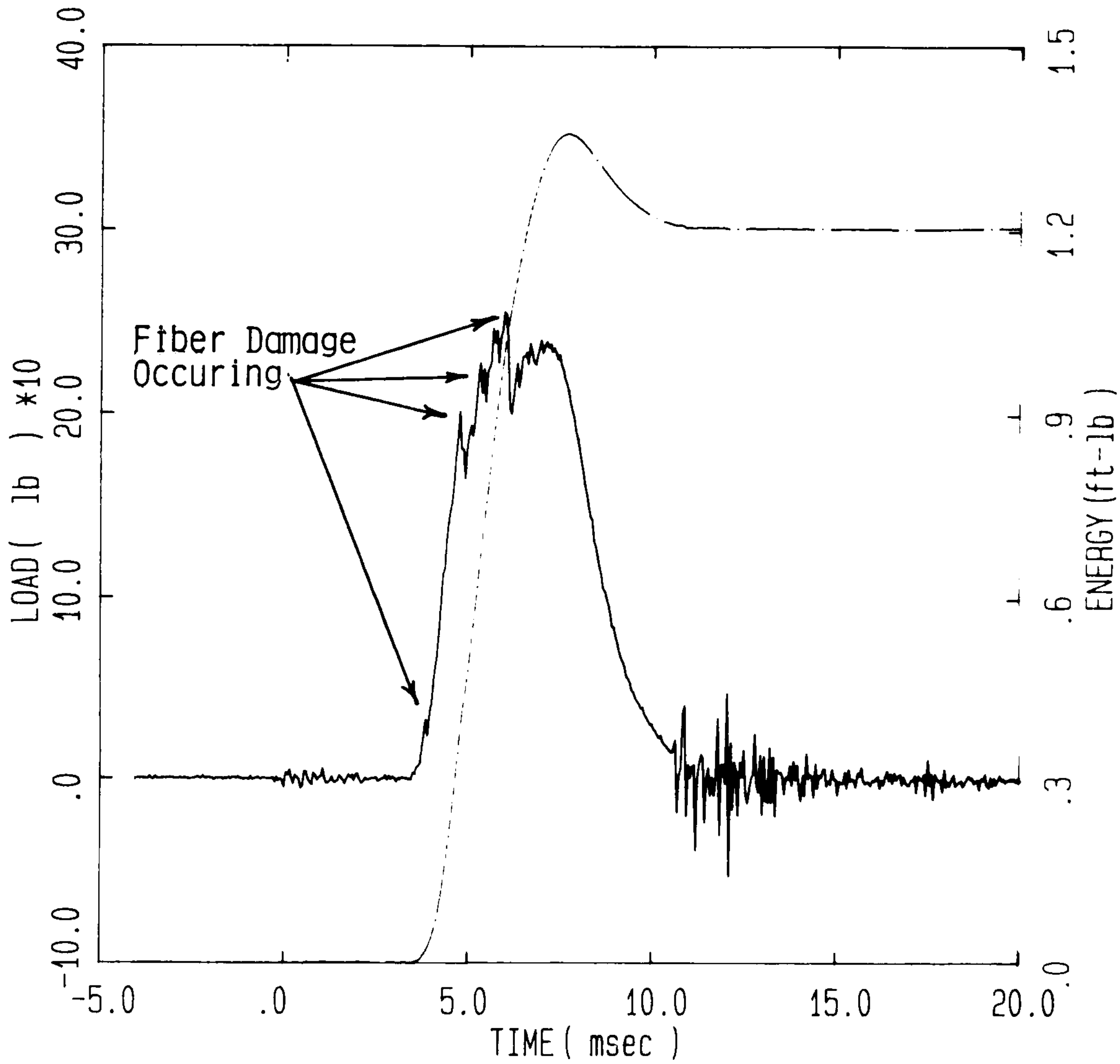
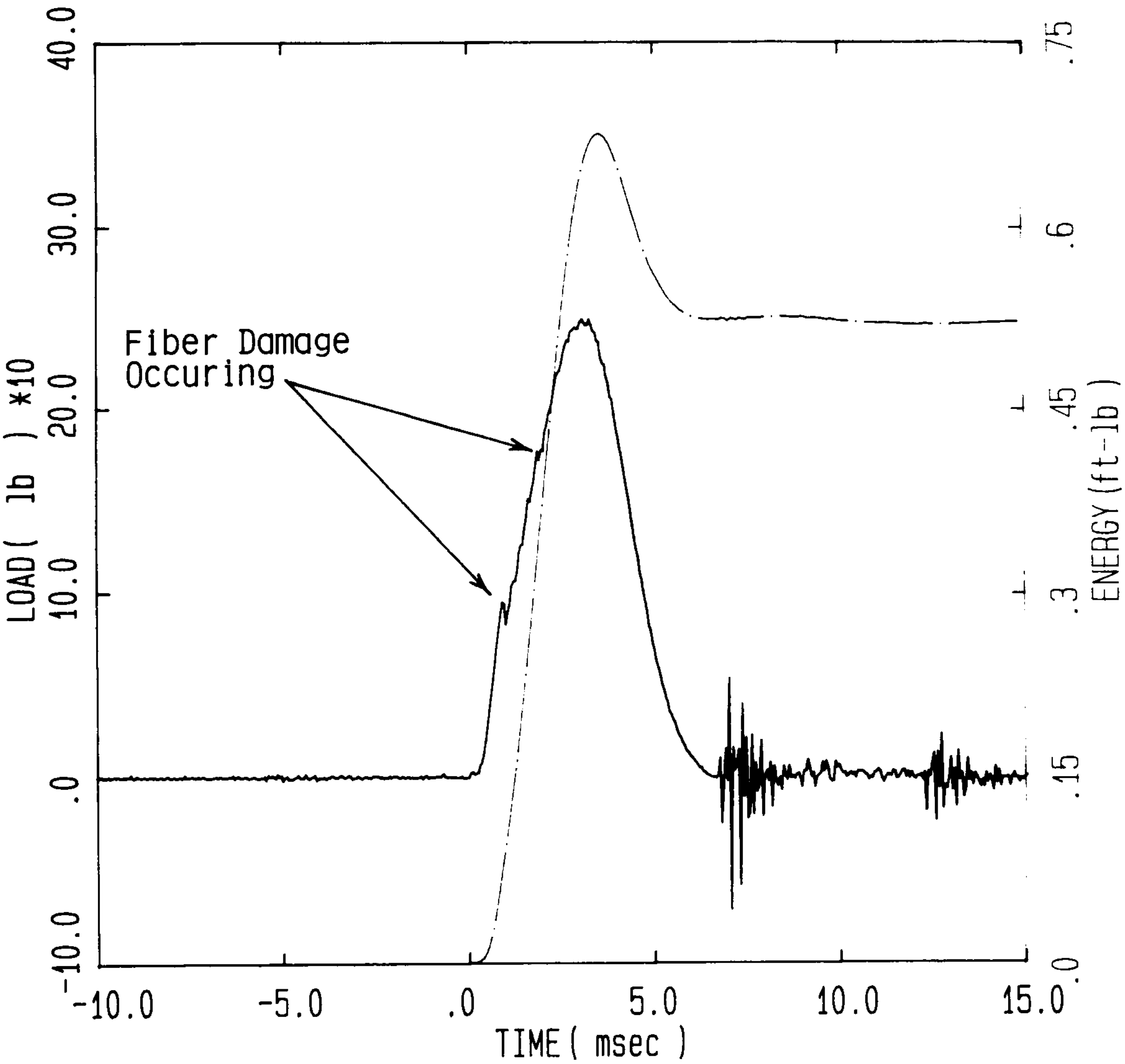
Figure VI-1.
Plot of Impact Load and Impact Energy vs. Time for a Unidirectional Sample. Drop Height of 2.5 inches.



Specimen Id	Temp (f)	Veloc. (ft/sec)	Energy (ft-lb)	Time (msec) Max Ld	Total	Load (lb) Max	Energy (ft-lb) Maxld	Total
40	70.	3.48	1.22	5.95	10.70	255.3	.982	1.209

Figure VI-2.
Plot of Impact Load and Impact Energy vs. Time for a $2[\pm45^\circ]_s$ Laminate. Drop Height of 1.25 inches.



Specimen Id	Temp (f)	Veloc. (ft/sec)	Energy (ft-lb)	Time (msec) Max Ld	Total	Load (lb) Max	Energy (ft-lb) Maxld	Total
08	70.	2.52	.64	3.05	6.55	248.8	.640	.524

Figure VI-3.
Plot of Ultimate Tensile Stress vs. Impact Energy for Unidirectional Graphite/Epoxy.

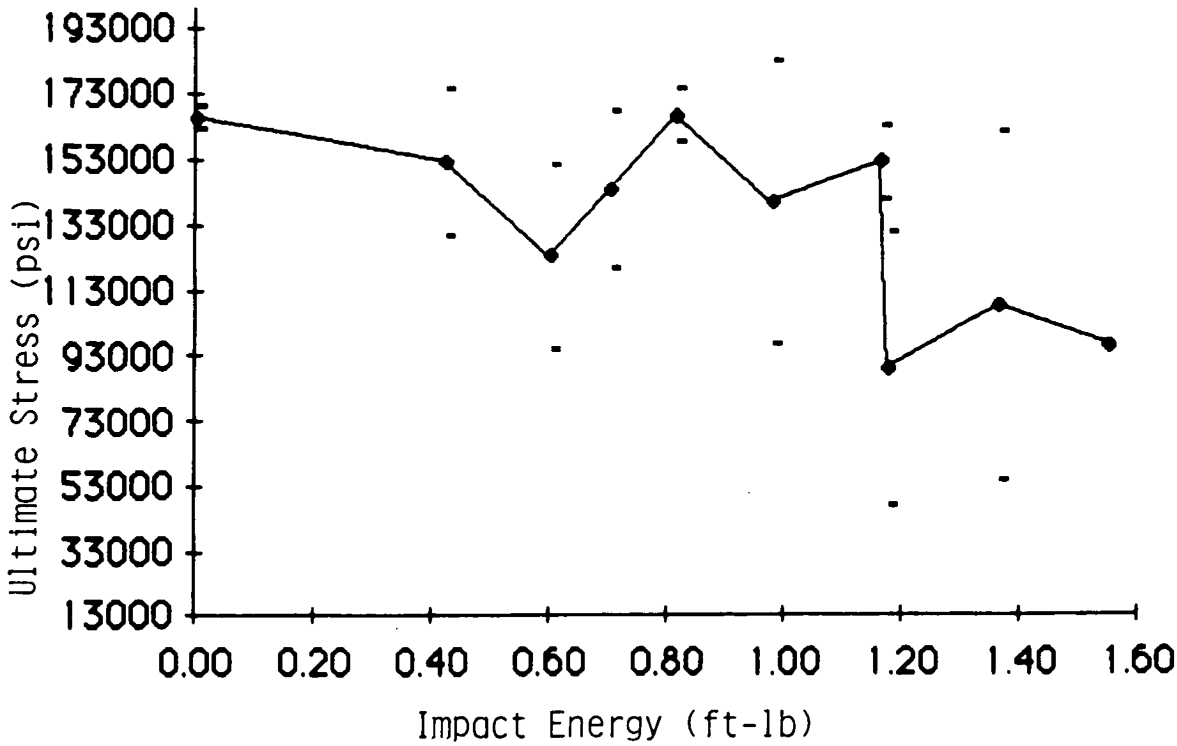


Figure VI-4.
Plot of Modulus, E_1, vs. Impact Energy
for Unidirectional Graphite/Epoxy.

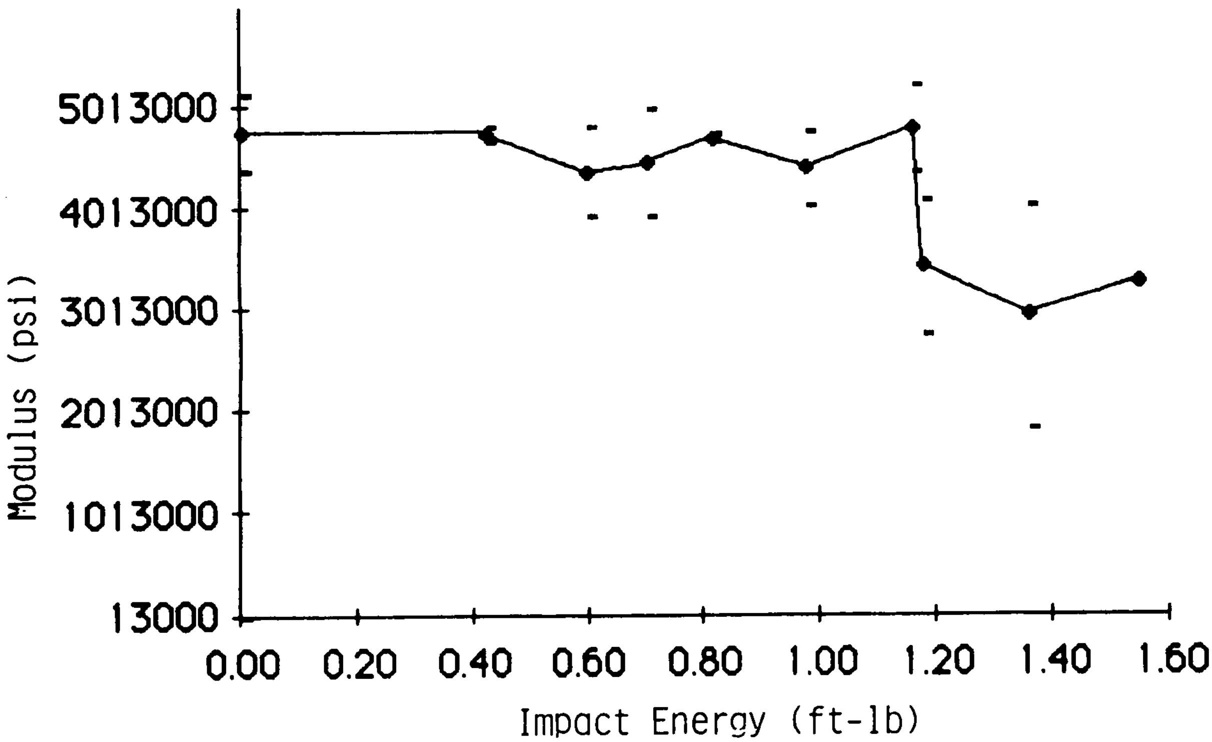


Figure VI-5.
Plot of Ultimate Tensile Stress vs. Impact Energy for a $2[\pm45]_s$ Graphite/Epoxy Laminate. VI-14

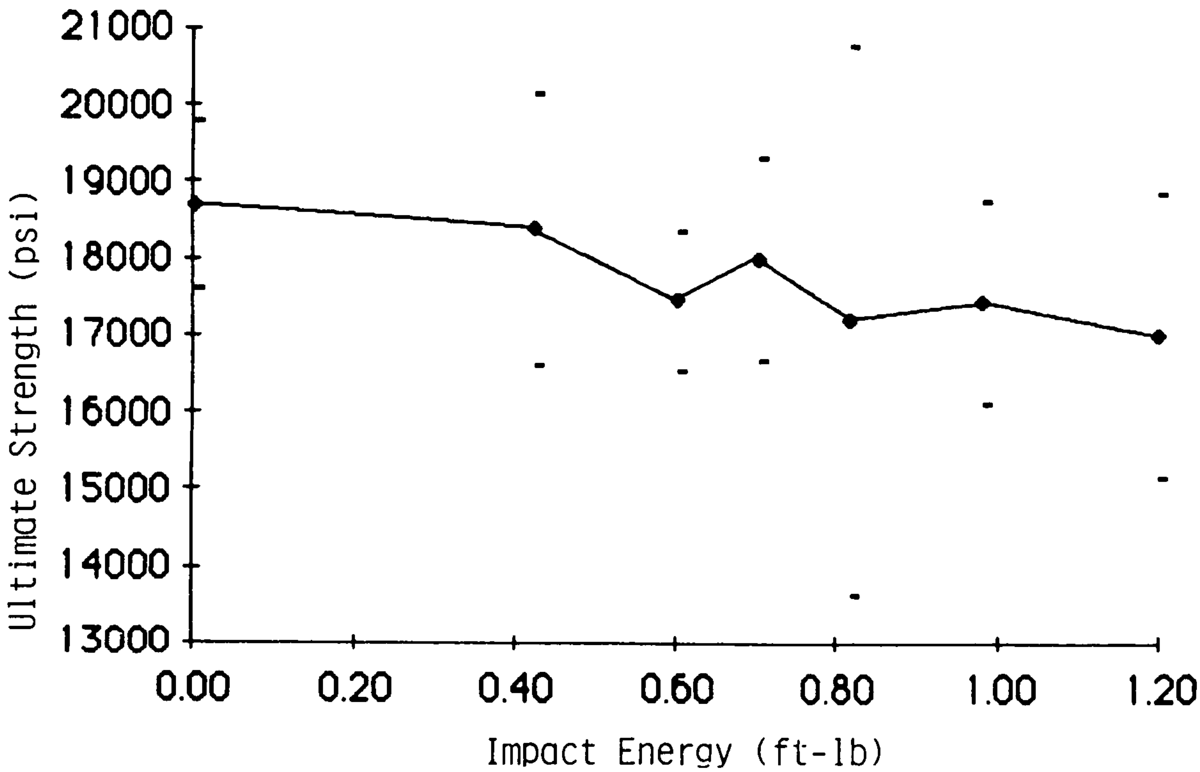


Figure VI-6.
Plot of Modulus, E_x, vs. Impact Energy for a $2[\pm 45]_s$ Graphite/Epoxy Laminate (x is the direction of the axis of the specimen). VI-15

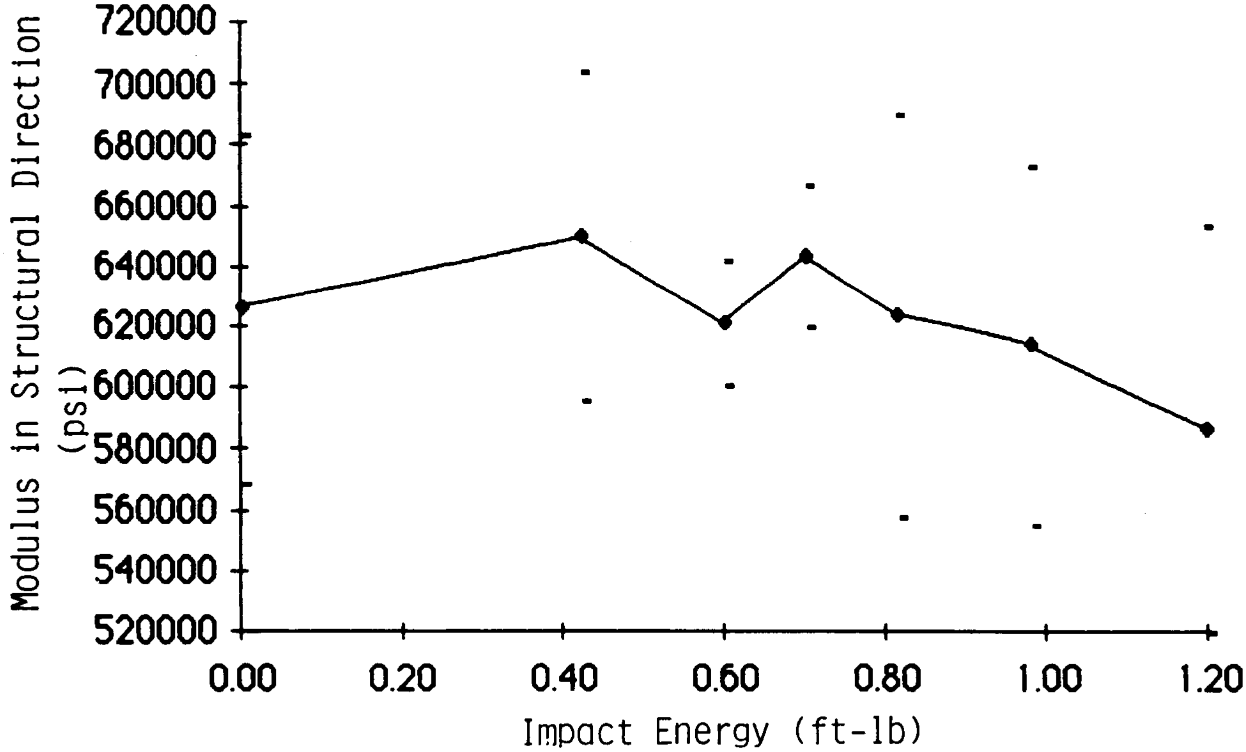


TABLE VI-1.
Results from Tensile Tests on Unidirectional Graphite/Epoxy (AS4/3501-6).

Drop Height in	Panel Number	Impact Energy ft-lb	Ultimate Stress kpsi	Modulus Mpsi
0.00	2	0.00	167.1	4.49
	3	0.00	169.3	5.02
	Average	0.00	166.2	4.75
1.00	1	0.52	170.3	4.78
	2	0.45	127.3	4.79
	3	0.44	160.5	4.66
	Average	0.46	152.7	4.74
1.25	1	0.61	155.7	4.87
	2	0.60	102.5	4.06
	3	0.55	113.1	4.19
	Average	0.59	123.8	4.37
1.50	1	0.72	153.8	4.84
	2	0.74	161.5	4.66
	3	0.76	116.5	3.86
	Average	0.74	143.9	4.46
1.75	1	0.87	175.0	4.70
	2	0.84	167.2	4.72
	3	0.95	158.8	4.64
	Average	0.87	167.0	4.69
2.00	1	0.95	138.9	4.39
	2	1.01	98.0	4.05
	3	0.99	184.0	4.78
	Average	0.98	140.3	4.41
2.25	1	1.14	158.9	5.14
	2	1.12	159.2	4.32
	3	1.09	139.2	4.90
	Average	1.12	152.4	4.79
2.50	1	1.18	136.6	4.19
	2	1.22	75.0	3.09
	3	1.13	57.1	3.00
	Average	1.18	152.7	3.43
2.75	1	1.37	59.9	1.84
	2	1.36	165.9	4.03
	3	1.36	100.3	2.96
	Average	1.36	108.7	2.94
3.00	3	1.55	96.7	3.27

TABLE VI-2.
Results from Tensile Tests on $2[\pm45]_s$
Graphite/Epoxy (AS4/3501-6) Laminates.

Drop Height in	Panel Number	Impact Energy ft-lb	Ultimate Stress kpsi	Modulus kpsi
0.00	1	0.00	18.8	
	2	0.00	19.9	640.
	3	0.00	18.9	675.
	4	0.00	17.3	563.
	Average	0.00	18.7	626.
1.00	1	0.42	17.6	578.
	2	0.45	21.0	706.
	3	0.41	17.8	672.
	4	0.41	17.1	645.
	Average	0.42	18.4	650.
1.25	1	0.56	17.9	631.
	2	0.64	18.5	614.
	3	0.61	17.3	596.
	4	0.59	16.3	645.
	Average	0.60	17.5	621.
1.50	1	0.70	16.8	620.
	2	0.75	19.7	671.
	3	0.64	18.5	628.
	4	0.72	17.1	655.
	Average	0.72	18.0	643.
1.75	1	0.83	18.0	651.
	2	0.72	20.5	642.
	3	0.80	18.2	675.
	4	0.91	12.1	527.
	Average	0.87	17.2	624.
2.00	1	1.00	17.3	624.
	2	0.99	19.0	658.
	3	0.97	17.8	648.
	4	0.96	15.8	528.
	Average	0.98	17.5	615.
2.25	1	1.10	17.4	648.
	2	1.09	19.5	610.
	3	1.48	15.5	597.
	4	1.12	15.7	492.
	Average	1.36	17.0	587.

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