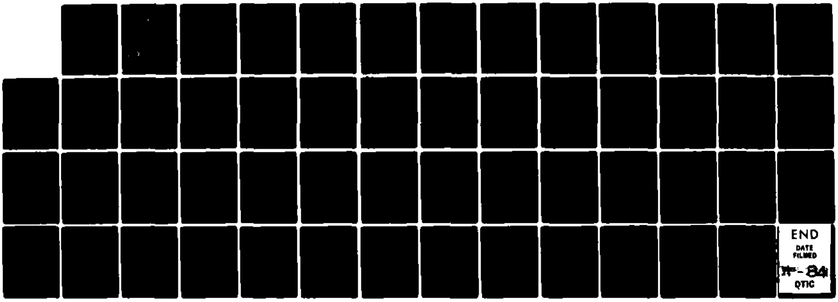
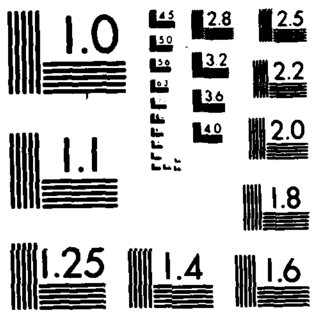
AD-A136 334 DETERMINATION OF THE EFFECT OF STRAIN RATE ON THE MECHANICAL PROPERTIES O..(U) NAVAL AIR DEVELOPMENT CENTER WARMINSTER PA AIRCRAFT AND CREW S.. J M ALPER 1/1

UNCLASSIFIED 01 MAY 83 NADC-83134-60 F/G 11/4 NL





MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

REPORT NO. NADC-83134-60

DETERMINATION OF THE EFFECT OF STRAIN RATE ON THE MECHANICAL PROPERTIES OF GRAPHITE/EPOXY LAMINATES

James M. Alper (Code 6043)
Aircraft and Crew Systems Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, PA 18974

1 MAY 1983

FINAL REPORT
Program Element No. 61152N
Airtask No. 2R00001, 2R02204
Work Unit No. GC122

Approved For Public Release; Distribution Unlimited

Prepared For
NAVAL AIR DEVELOPMENT CENTER
Department of the Navy
Warminster, PA 18974

N O T I C E S

REPORT NUMBERING SYSTEM - The numbering of technical project reports issued by the Naval Air Development Center is arranged for specific identification purposes. Each number consists of the Center acronym, the calendar year in which the number was assigned, the sequence number of the report within the specific calendar year, and the official 2-digit correspondence code of the Command Office or the Functional Directorate responsible for the report. For example: Report No. NADC-78015-20 indicates the fifteenth Center report for the year 1978, and prepared by the Systems Directorate. The numerical codes are as follows:

CODE	OFFICE OR DIRECTORATE
00	Commander, Naval Air Development Center
01	Technical Director, Naval Air Development Center
02	Comptroller
10	Directorate Command Projects
20	Systems Directorate
30	Sensors & Avionics Technology Directorate
40	Communication & Navigation Technology Directorate
50	Software Computer Directorate
60	Aircraft & Crew Systems Technology Directorate
70	Planning Assessment Resources
80	Engineering Support Group

PRODUCT ENDORSEMENT - The discussion or instructions concerning commercial products herein do not constitute an endorsement by the Government nor do they convey or imply the license or right to use such products.

APPROVED BY: T. S. GALLAGHER
CAPTAIN, USN

DATE: 18 August 1983

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NADC-83134-60

2. GOVT ACCESSION NO.
AD-A136 334

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Determination of the Effect of Strain Rate on the Mechanical Properties of Graphite/Epoxy Laminates

5. TYPE OF REPORT & PERIOD COVERED
Final Technical
1 Oct 1980 to 30 Sep 1982

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
James M. Alper

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Air Development Center
Code 6043
Warminster, Pennsylvania 18974

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
61152N, ZR00001,
ZR02204, GC122

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Air Development Center
Code 6043
Warminster, Pennsylvania 18974

12. REPORT DATE
1 May 1983

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Accession For	
NTIS GRA&I	☑
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

graphite/epoxy laminates; strain rate; static strength

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The main objective of this program was to experimentally evaluate the effect of strain rate on graphite/epoxy laminates. Specimens representing four laminates ($[0]_{24T}$, $[\pm45]_{12S}$, $[(\pm45/0_2)_3/90]_S$, and $[(\pm45/0/\pm45)_2/\pm45/90]_S$) were statically tested in one of two environments, room temperature dry or elevated temperature wet (200°F, 1% moisture content) at strain rates in either tension or compression which yielded failure times of .1 sec, 1 sec, 10 sec, and 100 sec. Results indicate that the laminates are more strain rate sensitive under the elevated

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20.

temperature wet environment and that laminates typical for Navy aircraft have a statistically significant strain rate effect only under the elevated temperature wet condition.

FOREWORD

This is the final report for the program entitled "Determination of the Effect of Strain Rate on the Mechanical Properties of Graphite/Epoxy Laminates."

The project was initiated by Mr. M. Rosenfeld, who was the principal investigator from October 1980, to September 1981. Dr. J. Alper was the principal investigator for the remainder of the program, October 1981, to September 1982.

The author expresses appreciation to Mr. M. Corrigan and Mr. R. Dalrymple for their efforts on specimen testing.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Graphite/epoxy composites are commonly used on Navy aircraft to reduce the weight of the structure and improve performance. As the aircraft are subjected to flight maneuvers, stresses and strains occur in the various components, dependent on the maneuver. The rate at which the stresses and strains are applied varies with the speed at which the maneuvers occur. Strain rates up to 5000 μstrain/sec. can be encountered during flight. It is possible that a given component was designed from information generated at a much slower or faster strain rate than it actually experiences. If the strength of the material is strain rate dependent, a component could be unconservatively designed. Consider for example, a study by Ryder and Walker(1). It was found that some graphite/epoxy coupons subjected to fatigue cycling failed in the first cycle at tensile strengths much less than those expected from static tensile testing of the same laminate. The strain rate for the fatigue test in these cases was at least 100 times greater than the strain rate for the static test. In the laboratory it is common to run fatigue tests in which composite coupons experience 100,000 μstrain/sec., while static tests are conducted at 100 μstrain/sec.

Also, considering that fatigue specimens tested at a high frequency are subject to strain rates which are higher than strain rates in specimens fatigued at lower frequencies, it can be speculated that strain rate sensitivity may have an effect on the fatigue life of graphite/epoxy laminates. It has been shown that under constant amplitude fatigue, specimens tested at one frequency can show life times three or four times greater than specimens tested at a different frequency (2-5).

The purpose of this research program was to experimentally investigate the effect of strain rate on the static strength of graphite/epoxy laminates.

In particular, layups were used representative of both fiber-dominated and matrix-dominated laminates. Specimens were tested statically at strain rates typical of those experienced by aircraft in flight and at rates commonly used in the laboratory.

Exposure to certain environments, such as high temperature and high humidity, can affect the strength of graphite/epoxy. To investigate this effect, both room temperature dry and elevated temperature wet (200°F, 1% moisture content) specimens were tested in this program.

EXPERIMENTAL PROCEDURE

TEST SPECIMENS

The specimens used in this program were fabricated by the Martin Marietta Corporation using AS-3501-6 material. Four graphite/epoxy laminates were used representing both fiber and matrix dominated layups: Laminate 1, $[0°]_{24T}$; Laminate 2, $[\pm 45]_{12S}$; Laminate 3, $[(\pm 45/0_2)_3/\overline{90}]_S$; and Laminate 4, $[(\pm 45/0/\pm 45)_2/\pm 45/\overline{90}]_S$. Laminates 3 and 4, respectively, represent typical fiber and matrix dominated layups used on Navy aircraft, and Laminates 1 and 2, respectively, are extreme cases of fiber and matrix-dominated layups which are used here to better emphasize any trends which may appear in the other two laminates.

A 25.4 mm (1 in) wide specimen with a 6.35 mm (0.25 in) diameter center hole, as shown in Figure 1, was used for strain rate testing both in tension and compression. An identical specimen without the center hole was used for material characterization. The center hole specimen insures that failure occurs at the middle of the specimen and not at the end tab. Specimens were reinforced with glass fiber reinforced plastic end tabs to prevent buckling under compression loading (see Figure 1).

EQUIPMENT

All specimens were tested in a MTS closed-loop servo-hydraulic test machine equipped with "Alignomatic" self-aligning hydraulic grips. Tests conducted at strain rates of 35000 μstrain/sec. or faster were monitored using a Nicolette digital oscilloscope. Tests at slower strain rates were monitored using a Hewlett Packard X-Y plotter.

TEST PROCEDURE

Twenty-four unnotched specimens were statically tested to determine initial strain rate behavior for the four laminates as a function of load rate. The MTS machine used in these tests had only load control. The test plan for these specimens is shown in Table I. Based on this information, strain rates were chosen for each laminate to provide failure times of 100 sec., 10 sec., 1 sec., and .1 sec. These represent strain rates in the approximate range of 100 μstrain/sec. to 100,000 μstrain/sec. and encompass those values that occur during laboratory static testing, maximum maneuver, and gust loads of Navy aircraft in flight, as well as typical laboratory fatigue testing and vibration loading in flight. The actual strain rate and number of specimens used in each case are shown in Table II.

ENVIRONMENTAL CONDITIONS

Specimens were tested both at room temperature dry (RTD) and elevated temperature wet (ETW: 200°F, 1% moisture content) conditions. The RTD environment is a standard environment for evaluating material properties, and the ETW condition is about the most severe environment that the graphite/epoxy would be exposed to on the aircraft. In the latter environment (200°F, 1% moisture content), matrix-dominated laminates may lose up to 20% of their RTD static strength.

Specimens for the ETW test were in an environmental chamber 44 days at 170°F and 90% R.H. to obtain 1% moisture content. Traveler specimens 25.4 mm (1 in) x 25.4 mm (1 in) with a 6.35 mm (0.25 in) diameter hole and two edges blocked off by lead tape were used to monitor the moisture content. The lead tape prevented moisture from entering those edges.

	T in.	T mm.
LAMINATES 1 AND 2	.125	3.17
LAMINATES 3 AND 4	.130	3.30

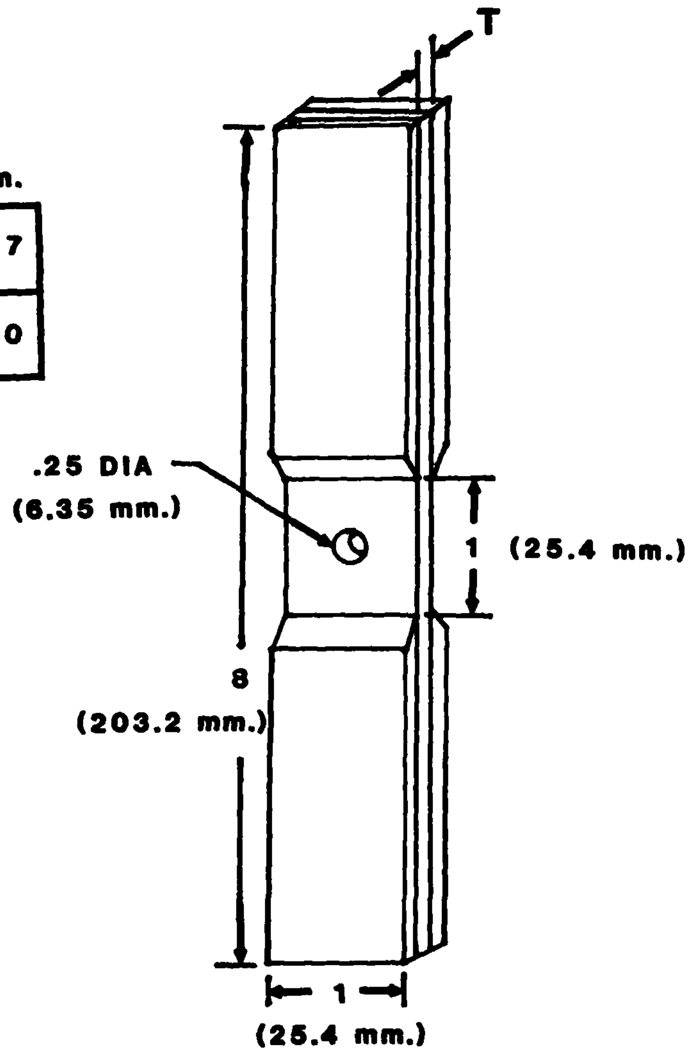


Figure 1. SPECIMEN GEOMETRY

TABLE I: TEST PLAN FOR UNNOTCHED SPECIMENS

A. RTD

Case	Laminate (1)	Test Rate (lb/sec)	Maximum Strain Before Unloading Specimen (μstrain)
1	2, 4	20	2000
2	1, 2, 3, 4	200	2000
3	1, 2, 3, 4	2000	2000
4	1, 3	20000	2000
5	1, 2, 3, 4	200	Reload all specimens from Case 2 to failure.

B. ETW (2)

Case	Laminate (1)	Test Rate (lb/sec)	Maximum Strain
1	1, 2, 3, 4	200	Test to failure
2	1, 2, 3, 4	2000	Test to failure

(1) Two specimens were tested from each laminate listed at each test rate: one in tension, and one in compression.

(2) These specimens were subjected to the RTD tests to 2000 μstrain in Part A.

TABLE II. TEST PLAN FOR NOTCHED SPECIMENS (1)

Laminate (2)	Test Condition (3)	Strain Rate (μstrain/sec.): No. of specimens Based on Time to Failure			
		.1 sec.	1 sec.	10 sec.	100 sec.
1	RTD-T	200000:10(4)	9600:7	960:7	96:10
1	RTD-C	71300:10	7130:7	713:7	71.3:10
1	ETW-C	35000:9	3500:7	350:7	35:9
2	RTD-T	148000:10	14800:7	1480:7	148:10
2	ETW-T	193000:10	–	–	193:10
2	RTD-C	96500:10	9650:7	965:7	96.5:10
2	ETW-C	77000:9	–	–	77:10
3	RTD-T	142000:10	14200:7	1420:7	142:10
3	ETW-T	144000:11	–	–	144:11
3	RTD-C	65300:10	6530:7	653:7	65.3:10
3	ETW-C	43500:11	–	–	43.5:11
4	RTD-T	214000:10	21400:7	2140:7	214:10
4	ETW-T	141000:11	–	–	141:11
4	RTD-C	98700:10	9870:7	987:7	98.7:10
4	ETW-C	61500:10	–	–	61.5:9

(1) Does not include specimens that failed due to end tab failure or machine malfunction.

(2) Laminate 1 – $(0)_{24T}$, Laminate 2 – $(\pm 45)_{12S}$,

Laminate 3 – $[(\pm 45/0_2)_3/\overline{90}]_s$,

Laminate 4 – $[(\pm 45/0/\pm 45)_2/\pm 45/\overline{90}]_s$

(3) RTD – room temperature dry, ETW – elevated temperature wet (200°F, 1% moisture content), T - tension, C - compression

(4) 200000 was used instead of 96000 because of an improper machine setting during the actual test.

Prior to testing, the specimens were removed from the environmental chamber and placed directly in the MTS grips. A quartz lamp was used to bring the temperature of the specimen up to 200°F. A thermocouple attached to the back of the specimen was used to monitor the temperature. Insulation placed around the load cell and grips of the test machine ensured that machine accuracy would not be affected by the testing temperature. As soon as the specimen achieved the desired temperature, the test was started.

TEST RESULTS AND DISCUSSION

SUMMARY OF UNNOTCHED SPECIMENS

The unnotched specimens were used to characterize the material and develop a relationship between strain rate and time to failure. Table III shows the material characteristics for both RTD and ETW conditions. Appendix A contains a detailed presentation of the data. This information was used to extrapolate the relationship between initial strain rate and time to failure that was shown in the Test Plan, Table II.

SUMMARY OF NOTCHED SPECIMENS

Notched specimens were tested according to the Test Plan shown in Table II. Results for the RTD tests and ETW tests including the mean strength and standard deviation are shown, respectively, in Tables IV and V. All statistics are based on the normal distribution. Raw data for each test are presented in Appendix B.

DISCUSSION OF RESULTS

Results from the tests are presented in Figures 2 through 9. Each plot shows the statistical information generated from the tension and compression testing for each laminate. The mean ± one standard deviation is plotted for each strain rate tested. A linear regression fit is used as an indicator for the behavior of the means as the strain rate changes. Table VI represents the results of statistical significance testing. Statistical significance testing is used to determine if samples from the same laminate under identical test conditions except the strain rate (i.e. Laminate 1, RTD, tension) are from the same population. The method used for signficance testing was taken from MIL-HNBK 5 (6).

Figure 2 represents the RTD data for Laminate 1 (100/0/0). In tension, the trend of the means indicates an increase in strength as the strain rate decreases, while in compression there is an increase in strength as the strain rate increases. These trends may be due to the matrix behavior, since cracks have more time to grow at slower strain rates. Under tension load, cracking could allow misaligned or kinked fibers to straighten out, while under compression loading cracking could lead to greater buckling due to increased local instabilities. The results shown in Table VI indicate a statistically significant strain rate effect in compression but not in tension.

RTD data for Laminate 2 (0/100/0) is presented on Figure 3. Based on the linear regression fit of the means, the strength increases as the strain rate increases for both tension and compression. Since this is a matrix dominated layup, crack growth at slower strain rates could lead to earlier failures. The significance test in Table VI indicates a statistically significant effect for Laminate 2 under tension but not compression.

Results of the fiber-dominated Laminate 3 (48/48/4) at the RTD condition are shown in Figure 4. Although there is a slight tendency toward increased strength at slower strain rates for both tension and compression, neither case is statistically significant.

For the matrix-dominated Laminate 4 (16/80/4) at RTD, the results shown in Figure 5 indicate an increased strength at the faster strain rates in tension and at the slower strain rates in compression. However, neither case is statistically significant.

TABLE III: EXPERIMENTAL RESULTS OF UNNOTCHED SPECIMENS

A. Tension

Laminate	Modulus, Ex (MSI(GPa))		Poisson Ratio νxy	Ultimate Strength KSI(MPa))	
	RTD	ETW	RTD	RTD	ETW
1 (100/0/0)	20.4(141)	18.8(130)	.33	190(1310)	180(1241)
2 (0/100/0)	2.9(20)	1.3(9)	.83	43(296)	31(214)
3 (48/48/4)	10.0(69)	10.4(72)	.57	136(938)	125(862)
4 (16/80/4)	5.5(38)	4.8(33)	.69	83(572)	72(496)

B. Compression

Laminate	Modulus, Ex (MSI (GPa))		Poisson Ratio νxy	Ultimate Strength (KSI (MPa))	
	RTD	ETW	RTD	RTD	ETW
1 (100/0/0)	16.7(115)	19.3(133)	.29	83(572)	68(469)
2 (0/100/0)	2.4(17)	1.7(12)	.72	23(159)	15.5(107)
3 (48/48/4)	8.3(57)	10.0(69)	.49	52(359)	45(310)
4 (16/80/4)	4.9(34)	5.3(37)	.59	45(310)	34(234)

TABLE IV: RESULTS OF RTD NOTCHED SPECIMENS

A. Tension

Laminate	Strain Rate μstrain/sec	Mean Strength X, KSI, (MPa)	Standard Deviation σ, KSI (MPa)
1 (100/0/0)	200000	271(1868)	15.8(109)
1	9600	283(1951)	13.1(90)
1	960	280(1930)	21.2(146)
1	96	293(2020)	21.4(148)
2 (0/100/0)	148000	35(241)	0.6(4.1)
2	14800	34(234)	0.71(4.9)
2	1480	33(228)	0.51(3.5)
2	148	32(221)	0.77(5.3)
3 (48/48/4)	142000	94(648)	4.9(33.8)
3	14200	98(676)	2.7(18.6)
3	1420	95(655)	4.4(30.3)
3	142	97(669)	2.3(15.9)
4 (16/80/4)	214000	55(379)	2.5(17.2)
4	21400	54(372)	1.2(8.3)
4	2140	53(365)	1.3(9.0)
4	214	53(365)	1.5(10.3)

B. Compression

Laminate	Strain Rate μstrain/sec	Mean Strength X, KSI (MPa)	Standard Deviation σ, KSI (MPa)
1 (100/0/0)	71300	-92(-634)	10.1(70)
1	7130	-95(-655)	3.5(24)
1	713	-95(-655)	2.9(20)
1	71.3	-84(-579)	10.1(70)
2 (0/100/0)	96500	-34(-234)	5.2(36)
2	9650	-31(-214)	1.9(13)
2	965	-31(-214)	2.3(16)
2	96.5	-33(-228)	3.1(21)
3 (48/48/4)	65300	-70(-483)	4.5(31)
3	6530	-68(-469)	4.9(34)
3	653	-72(-496)	5.1(35)
3	65.3	-74(-510)	2.9(20)
4 (16/80/4)	98700	-47(-324)	5.4(37)
4	9870	-46(-317)	5.2(36)
4	987	-51(-352)	3.4(23)
4	98.7	-49(-338)	2.6(18)

TABLE V: RESULTS OF ETW NOTCHED SPECIMENS

A. Tension

Laminate	Strain Rate μstrain/sec	Mean Strength X, KSI (MPa)	Standard Deviation σ, KSI (MPa)
2 (0/100/0)	193000	29(200)	1.4(10)
2	193	29(200)	0.84(6)
3 (48/48/4)	144000	114(786)	5.9(41)
3	144	116(800)	5.7(39)
4 (16/80/4)	141000	52(359)	1.2(8)
4	141	50(345)	1.6(11)

B. Compression

Laminate	Strain Rate μstrain/sec	Mean Strength X, KSI (MPa)	Standard Deviation σ, KSI (MPa)
1 (100/0/0)	35000	-59(-407)	13.0(90)
1	3500	-51(-352)	3.2(22)
1	350	-48(-330)	4.9(34)
1	35	-44(-303)	2.9(20)
2 (0/100/0)	77000	-20(-138)	1.04(7)
2	77	-16(-110)	0.67(5)
3 (48/48/4)	43500	-48(-331)	3.7(26)
3	43.5	-42(-290)	3.3(23)
4 (16/80/4)	61500	-32(-221)	2.3(16)
4	61.5	-26(-179)	.92(6)

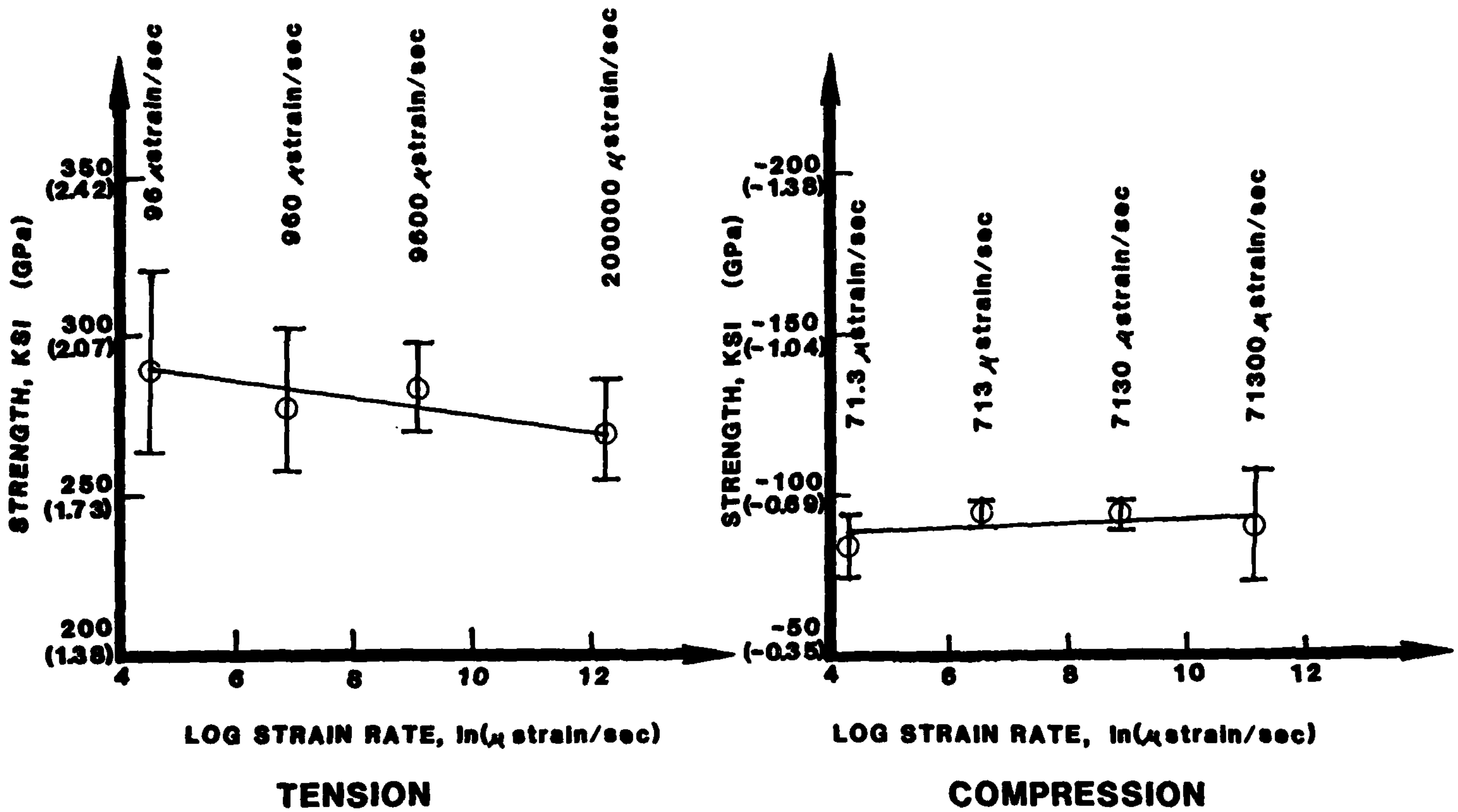


Figure 2. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 1 (100/0/0) RTD

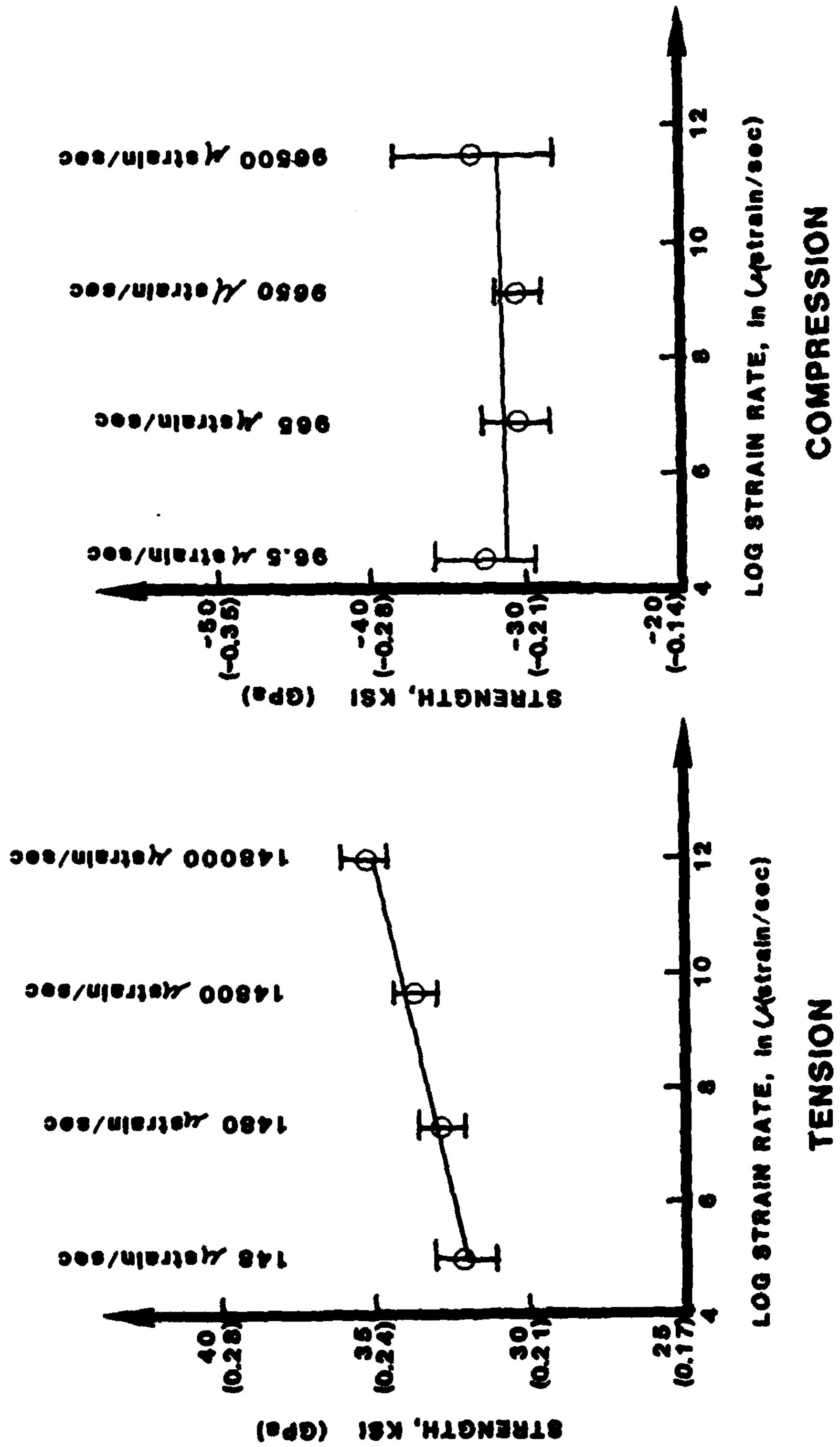


Figure 3. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 2 (0/100/0) RTD

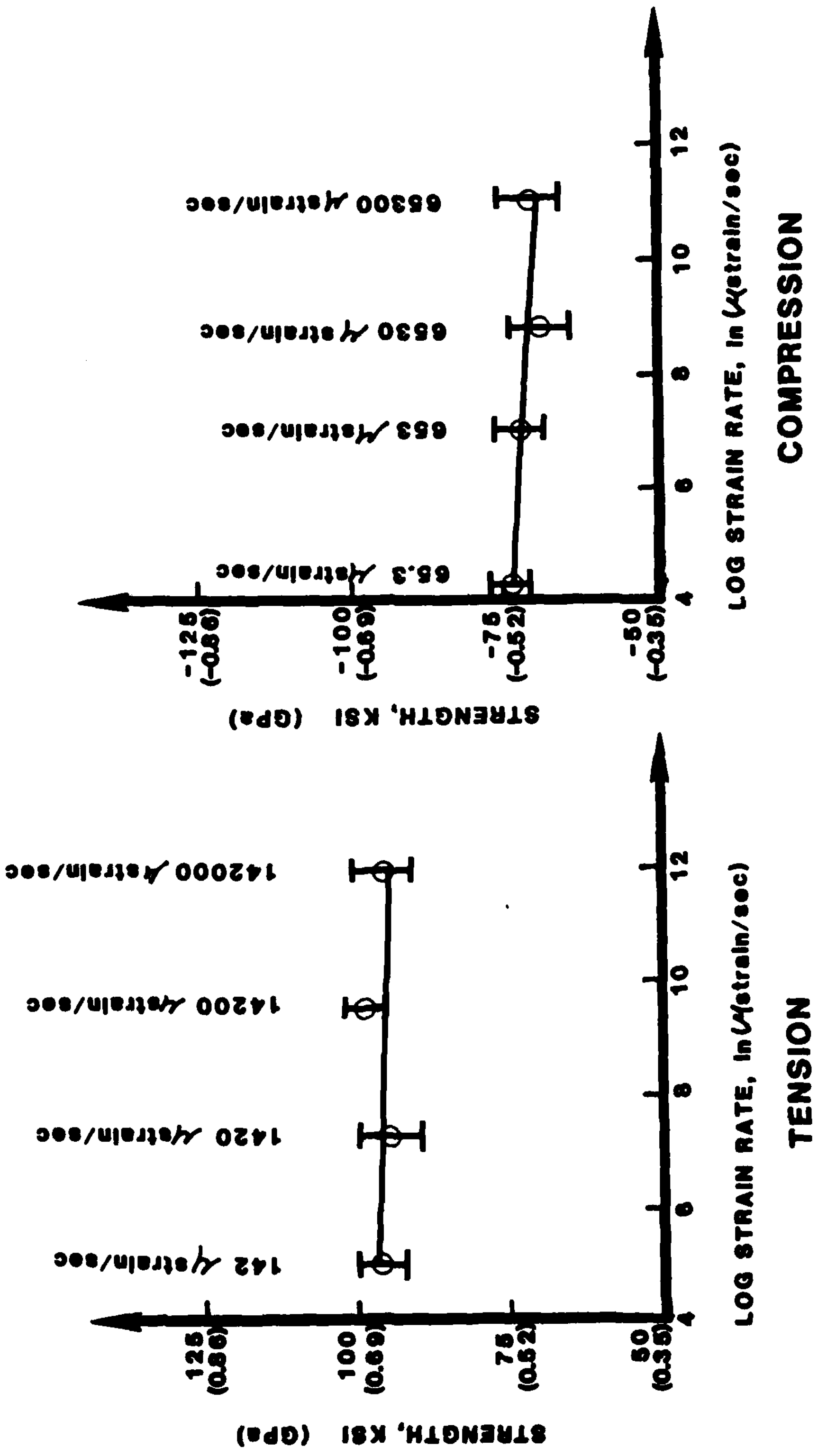


Figure 4. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 3 (48/48/4) RTD

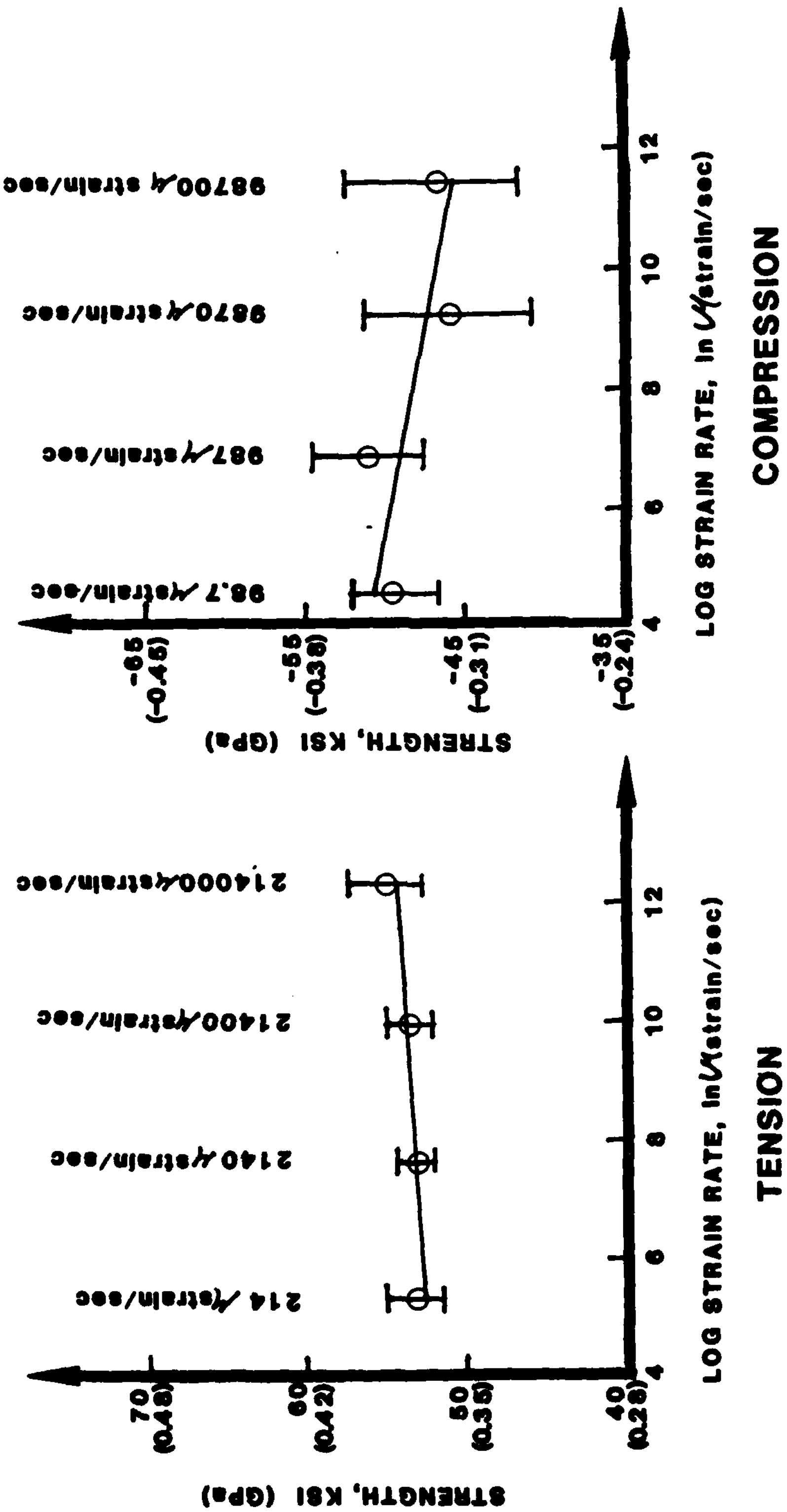


Figure 5. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 4 (16/80/4) RTD

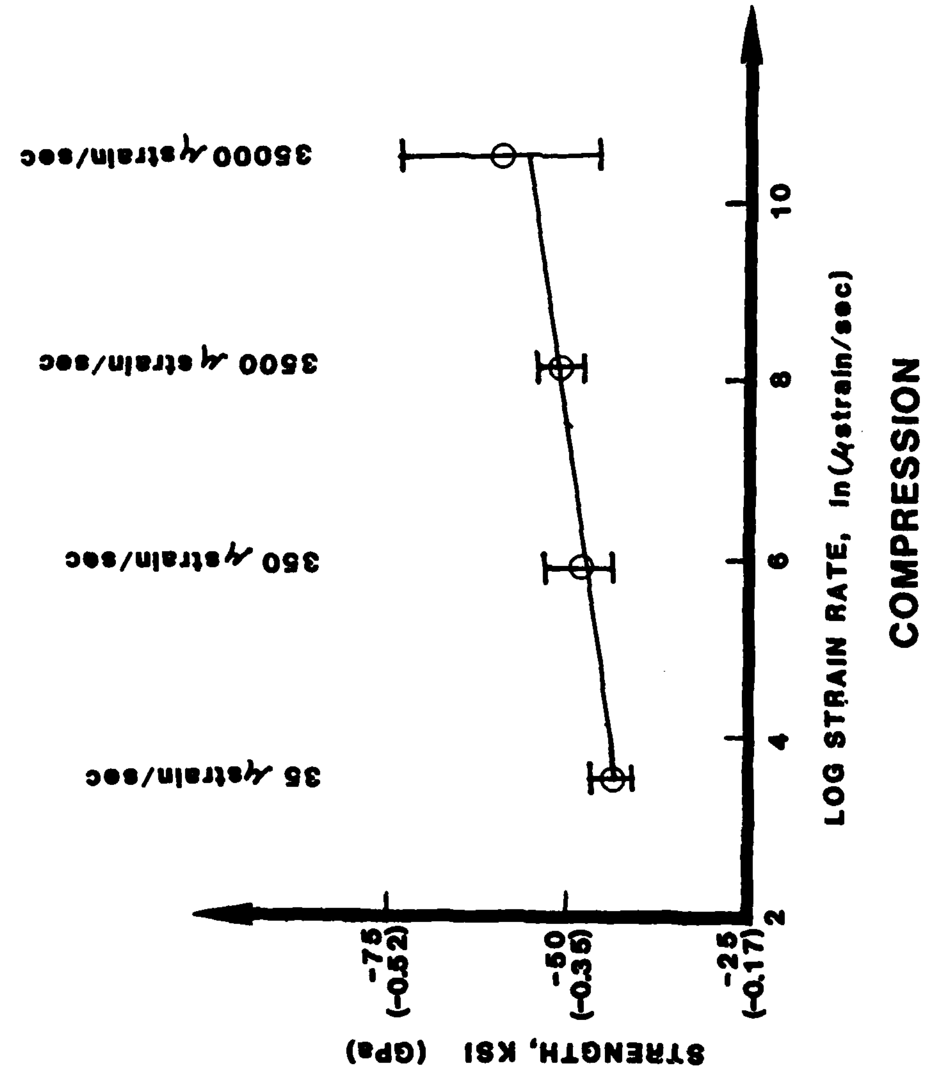


Figure 6. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 1 (100/0/0) ETW

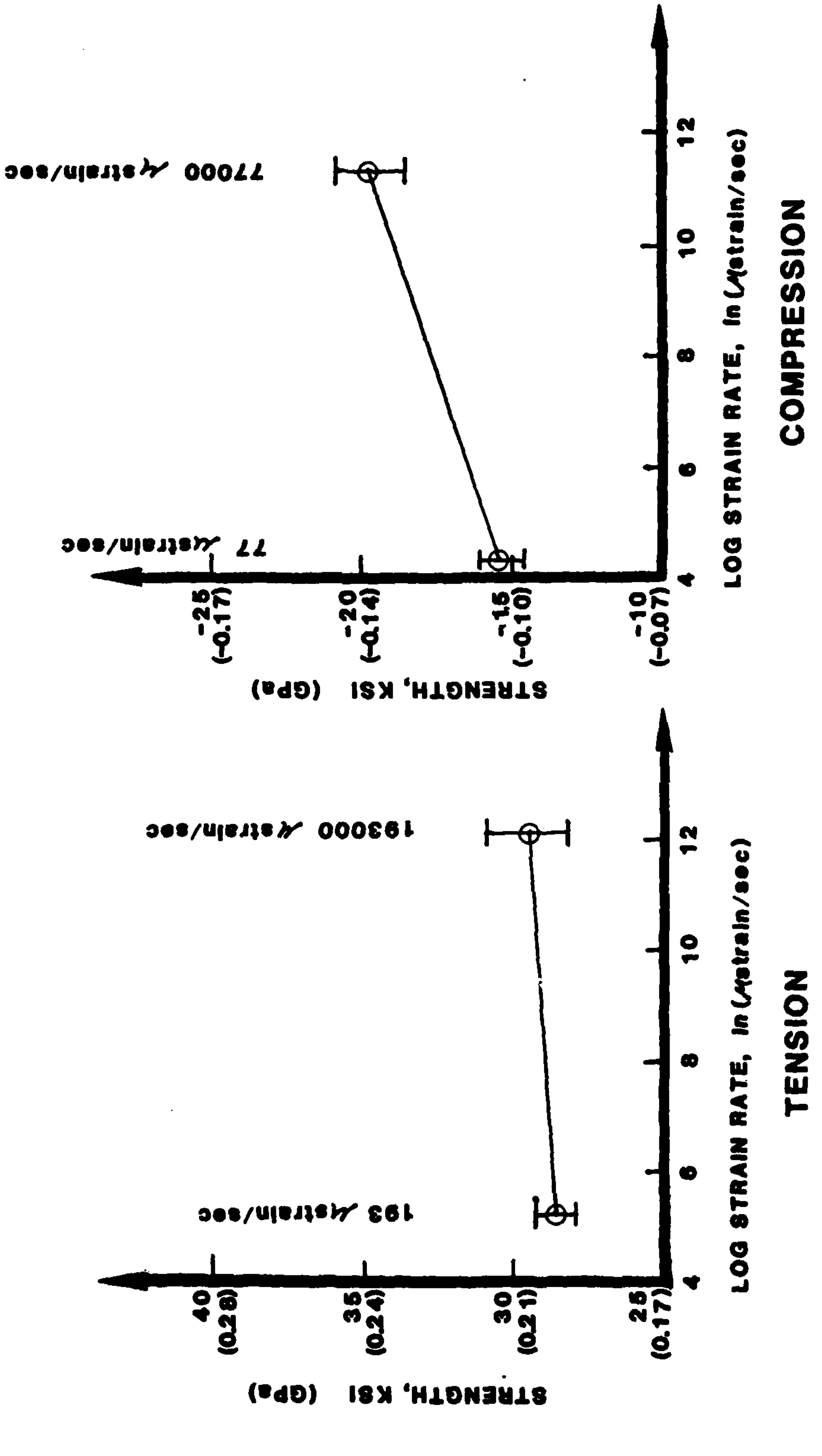


Figure 7. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 2 (0/100/0) ETW

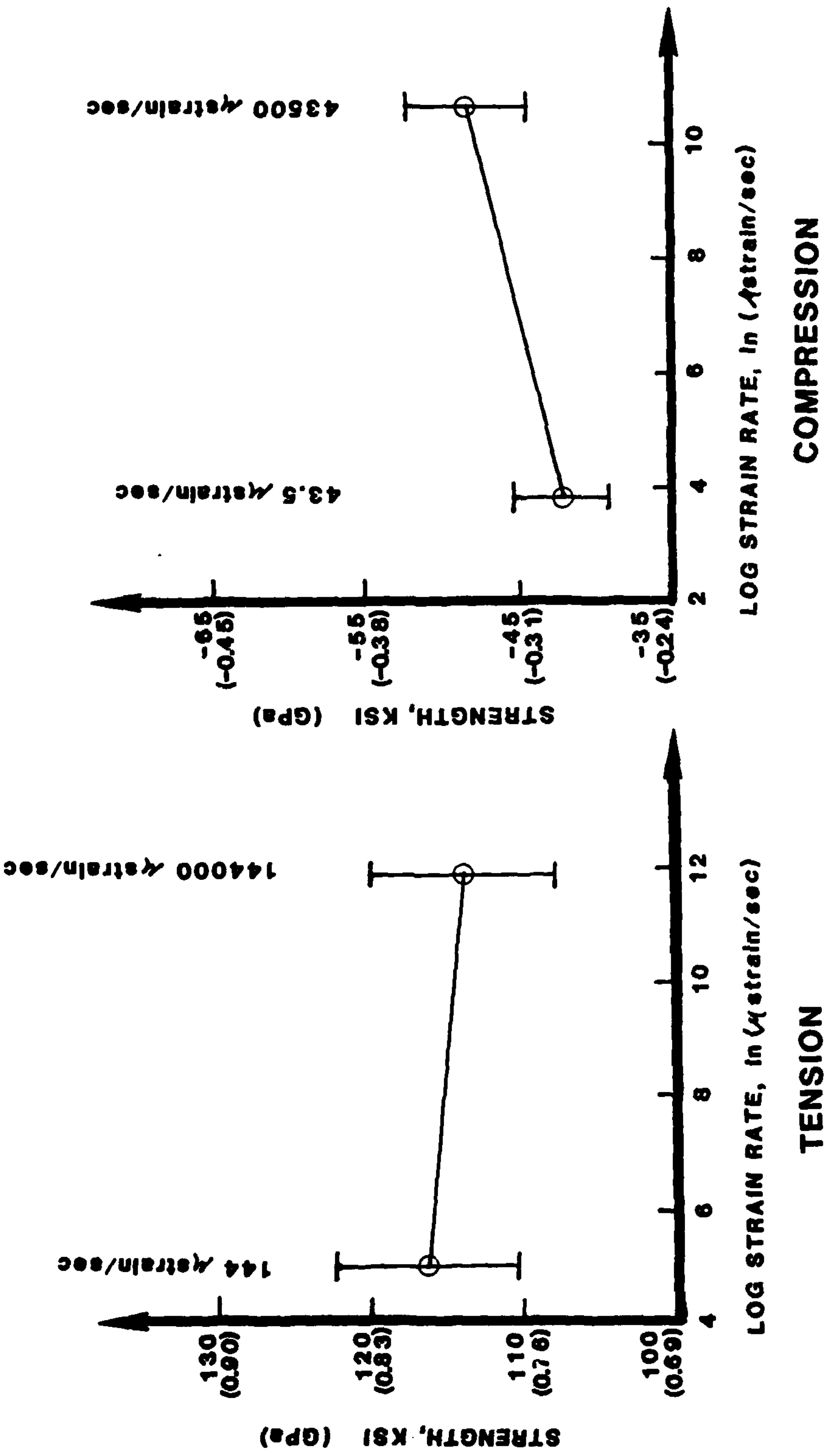


Figure 8. MEAN STRENGTH ± STANDARD DEVIATION
LAMINATE 3 (48/48/4) ETW

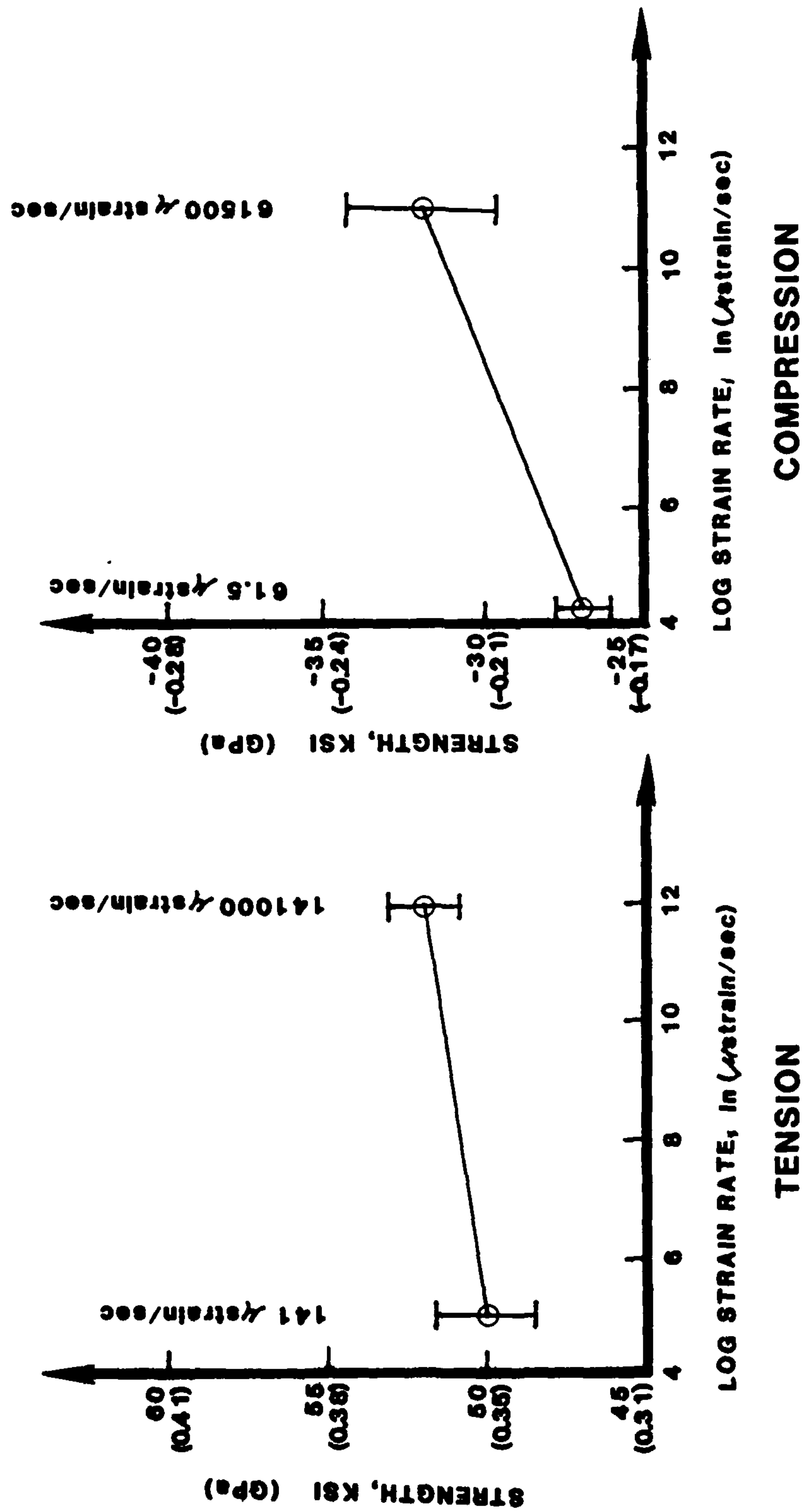


Figure 9. MEANS STRENGTH ± STANDARD DEVIATION
LAMINATE 4 (16/80/4) ETW

TABLE VI: RESULTS OF SIGNIFICANCE TEST

Laminate	Tension or Compression (T or C)	ETW or RTD	Based on time to failure (sec), are the two samples from the same population:					
			.1&1	.1&10	.1&100	1&10	1&100	10&100
1 (100/0/0)	T	RTD	Yes	Yes	No	Yes	Yes	Yes
1	C	RTD	No	No	Yes	Yes	No	No
1	C	ETW	No	No	No	Yes	No	Yes
2 (0/100/0)	T	RTD	No	No	No	No	No	Yes
2	C	RTD	No	Yes	Yes	Yes	Yes	Yes
2	T	ETW	–	–	Yes	–	–	–
2	C	ETW	–	–	No	–	–	–
3 (48/48/4)	T	RTD	Yes	Yes	No	Yes	Yes	Yes
3	C	RTD	Yes	Yes	No	Yes	No	Yes
3	T	ETW	–	–	Yes	–	–	–
3	C	ETW	–	–	No	–	–	–
4 (16/80/4)	T	RTD	Yes	Yes	Yes	Yes	Yes	Yes
4	C	RTD	Yes	Yes	No	Yes	Yes	Yes
4	T	ETW	–	–	No	–	–	–
4	C	ETW	–	–	No	–	–	–

At the RTD condition, the two laminates representative of those found on Navy aircraft (Laminates 3 and 4) do not indicate any statistically significant trends due to changes in strain rate.

At the ETW condition, Laminate 1 shows increased strength at the quicker strain rates for compression testing, Figure 6. From Table VI, it can be seen that these results are statistically significant.

Laminate 2 under the ETW condition also shows increased strength at the faster strain rates for both tension and compression, Figure 7. The results are statistically significant for compression but not in tension.

Prior to testing, it seemed plausible that the ETW environment would worsen any effects of strain rate seen at the RTD condition. Under tension testing, matrix dominated Laminate 2 showed results that were statistically significant for RTD but not for ETW, which disproves the above assumption.

Laminate 3 under the ETW condition, Figure 8, is stronger at the slower strain rate in tension and at the faster strain rate in compression. The strain rate effect in compression is statistically significant but not for the tension case. It is interesting to note that the trend of the compression behavior is different between RTD and ETW. RTD shows increased strength at slower strain rates while ETW shows increased strength at faster strain rates. Perhaps matrix degradation due to the ETW environment reduces the strength contribution from the 0° layers at slower strain therefore allowing this change in behavior.

Results of Laminate 4 at the ETW condition are shown in Figure 9. Both tension and compression cases showed increased strength at the faster strain rates. As shown in Table VI, both cases are statistically significant. With this laminate, as was the case with Laminate 3, the trend of the compression behavior is different for the ETW and RTD conditions. At RTD there is increased strength at the slower strain rate, and at ETW there is increased strength at the quicker strain rates.

SUMMARY AND CONCLUSIONS

The strain rate sensitivity of four laminates has been experimentally evaluated for both static tension and compression at two different environments, RTD and ETW (200°F, 1% moisture content). The layups were: Laminate 1, $[0]_{24T}$; Laminate 2, $[\pm 45]_{12S}$; Laminate 3, $[(\pm 45/0_2)_3 / \overline{90}]_S$; and Laminate 4, $[(\pm 45/0/\pm 45)_2 / \pm 45/\overline{90}]_S$. Strain rates used for RTD testing were chosen to simulate failure times of .1 sec., 1 sec., 10 sec., and 100 sec. For ETW tests, strain rates were chosen to simulate failure times of .1 sec. and 100 sec.

RTD Tests: Based on the linear regression fit of the mean strengths, the following trends appear:

Tension

1) Matrix-dominated layups (Laminates 2 and 4) are stronger at faster strain rates.

2) Fiber-dominated layups (Laminates 1 and 3) are stronger at slower strain rates.

Compression

1) Laminates 1 and 2 are stronger at faster strain rates.

2) Laminates 3 and 4 are stronger at slower strain rates.

Significance testing of the means and standard deviations indicate that there was a statistically significant strain rate effect on only two cases, Laminate 1 (compression) and Laminate 2 (tension). Both have matrix-dominated failure modes.

ETW Tests: Based on the linear regression fit of the mean strengths, the following trends appear:

Tension

1) Matrix-dominated layups (Laminates 2 and 4) are stronger at faster strain rates.

2) Fiber-dominated layup (Laminate 3) is stronger at the slower strain rate.

Compression

1) All laminates are stronger at the faster strain rates. Significance testing of the means and standard deviations indicate that strain rate had a statistically significant effect on matrix-dominated Laminate 4 in tension and on all of the laminates in comparison.

Apparently, the matrix degradation that occurs during exposure to the ETW environment makes the laminates more strain rate sensitive than the RTD environment.

Laminates common to Navy aircraft (Laminate 3 and 4) show statistically significant strain rate effects only under the ETW environment. Compression testing was most severe indicating increases in mean strength of 16.5% for Laminate 3 and 12.5% for Laminate 4 at the faster strain rates. However, since ultimate strength testing is conducted in the range of strain rates which yielded lower strengths for typical Navy laminates, the results of this program indicate that static test data used for aircraft design is conservative.

REFERENCES

1. Ryder, J. T. and Walker, E. K., Ascertainment of the Effect of Compressive Loading on the Fatigue Lifetime of Graphite Epoxy Laminates for Structural Applications, AFML-TR-76-241, December, 1976.

2. Sun, C. T. and Chan, W. S., "Frequency Effect on the Fatigue Life of a Laminated Composite," Composite Materials: Testing and Design (Fifth Conference), ASTM STP 674, 1979, pp. 418-430.

3. Saff, C.R., Effects of Layup and Loading Frequency on Fatigue Life of Graphite/Epoxy, NADC-81017-60, October, 1982.

4. Rosenfeld, M. S. and Gause, L. W., "Compression Fatigue Behavior of Graphite/Epoxy in the Presence of Stress Raisers," Fatigue of Fibrous Composite Materials, ASTM STP 723, 1981.

5. Sendeckyj, G. P. and Stalnaker, H.D., "Effect of Time at Load on Fatigue Response of $(0/\pm45/90)_{s}$ 2 T300/5208 Graphite-Epoxy Laminate," Composite Materials: Testing and Design (Fourth Conference), ASTM STP617, 1977, pp. 39-52.

6. MIL-HABK-5C, *Metallic Materials and Elements for Aerospace Vehicle Structures*, pp. 9.94-9.97.

APPENDIX A

MATERIAL CHARACTERIZATION

APPENDIX A: MATERIAL CHARACTERIZATION

A. RTD – Specimens

Specimen	Max. Stress prior to unloading, KSI (MPa)	Max. Strain prior to unloading, μstrain	Load Rate, lb/sec (kN/sec)	Time to Max. Strain, sec.	Initial Modulus, Ex, MSI (GPa)	Poisson Ratio νxy	Initial Strain Rate, μstrain/sec.
IL3	37.7 (260)	1900	200 (.89)	23.5	20.3 (140)	0.30	80.9
1E1	37.7 (260)	1850	2000 (8.9)	2.35	20.7 (143)	0.39	787
1D4	37.7 (260)	1900	20000 (89)	.34	20.2 (139)	0.32	5590
2G3	4.3 (29.6)	1487	20 (.089)	32.6	2.9 (20)	0.82	45.7
2A2	4.3 (29.6)	1487	200 (.89)	2.64	2.9 (20)	0.84	563
2F2	4.3 (29.6)	1475	2000 (8.9)	.31	2.9 (20)	0.84	4760
3A1	21.5 (148)	2112	200 (.89)	14.3	10.1 (70)	0.57	148
3J3	21.5 (148)	1950	2000 (8.9)	1.45	10.5 (72)	0.59	1340
3D1	21.5 (148)	2313	20000 (89)	.24	9.5 (66)	0.56	9720
4B5	10.6 (73)	1863	20 (.089)	97.0	5.8 (40)	0.70	19.2
4I6	10.6 (73)	1925	200 (.89)	6.9	5.3 (37)	0.71	281
4D8	10.6 (73)	1925	2000 (8.9)	.70	5.5 (38)	0.67	2750
1AF5	-31.5 (-217)	-2000	-20000 (-89)	.22	15.7 (108)	0.27	-9090
1AE2	-31.5 (-217)	-2033	-2000 (-8.9)	1.86	15.2 (105)	0.30	-1090
1AC6	-31.5 (-217)	-1600	-200 (-.89)	22.75	19.1 (132)	0.31	-70.3
2AA1	-4.2 (-29)	-1712	-2000 (-8.9)	.33	2.5 (17)	0.72	-5190
2HH5	-4.2 (-29)	-1742	-200 (-.89)	2.41	2.4 (17)	0.72	-723
2EE9	-4.2 (-29)	-1675	-20 (-.089)	29.6	2.4 (17)	0.73	56.6
3EE9	-17.8 (-123)	-2108	-20000 (-89)	.19	8.3 (57)	0.50	11153
3GG8	-17.8 (-123)	-2100	-2000 (-8.9)	1.03	8.2 (57)	0.49	-2040
3FF1	-17.8 (-123)	-2133	-200 (-.89)	10.8	8.3 (57)	0.47	-198
4AA1	-9.1 (-62.7)	-1783	-2000 (-8.9)	.54	5.2 (36)	0.60	-3300
4GG9	-9.1 (-62.7)	-1867	-200 (-.89)	5.25	4.8 (33)	0.60	-356
4EE9	-9.1 (-62.7)	-1925	-20 (-.089)	84.1	4.7 (32)	0.58	-22.9

(1) First digit of specimen no. indicates laminate (i.e. specimen no. 1L3 is from Laminate 1)

B. RTD – Failure Data (1)

Specimen No.	Ultimate Strength KSI (MPa)	Time to Failure, sec.	Initial Strain Rate μstrain/sec.
1L3	190 (1310)	73.8	80.9
2A2	43 (296)	31	563
3A1	136 (938)	135	148
4I6	83 (572)	48.2	281
1AC6	-83 (-572)	45.4	-70.3
2HH5	-23 (-159)	22	-723
3FF1	-52 (-359)	33	-198
4GG9	-45 (-310)	33	-356

(1) All specimens were previously subjected to test in part A.

C. ETW – Failure Data (1)

Specimen No.	Ultimate Strength KSI (MPa)	Time to Failure, sec.	Initial Strain Rate, µstrain/sec	Initial Modulus, Ex, MSI (GPa)
1E1	180 (1241)	212	35.7	18.8 (130)
1D4	81 (558) (2)	9.2	410	18.8 (1[illegible]0)
2F2	31.7 (219)	2.0	13440	1.19 (8.[illegible])
2G3	30.8 (212)	19.8	975	1.38 (9.5)
3D1	139 (958)	9.9	Not available	Not available
3J3	111 (765) (2)	75	150	10.4 (71.7)
4B5	75.8 (523)	5.0	Not available	Not available
4D8	68.6 (473)	45.3	310	4.75 (32.7)
1AE2	-70.5 (-486)	43.4	-85	19.1 (132)
1AF5	-65.2 (-450)	4.2	-814	19.4 (134)
2EE9	-16.6 (-114)	8.3	-928	1.7 (11.7)
2AA1	-14.4 (-99)	1.0	Not Available	Not available
3EE9	-47.8 (-329)	3.0	-1450	10.6 (73)
3GG8	-42.2 (-291)	28.1	-154	9.4 (64.8)
4AA1	-32.5 (-224)	2.1	-2810	5.3 (36.5)
4EE9	-35.4 (-244)	23.0	-275	5.3 (36.5)

(1) All specimens were previously subjected to test in part A.

(2) End tab failure.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B

STRENGTH OF NOTCHED SPECIMENS

APPENDIX B – STRENGTH OF NOTCHED SPECIMENS

A. LAMINATE NO. 1 (100/0/0)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 200000 μSTRAIN/SEC:
10 SPECIMENS

289 (1996)	262 (1809)	246 (1697)	242 (1670)
268 (1851)	257 (1777)	243 (1679)	
265 (1830)	247 (1709)	242 (1673)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 9600 μSTRAIN/SEC:
7 SPECIMENS

287 (1983)	274 (1891)	270 (1863)	254 (1756)
282 (1947)	274 (1890)	265 (1833)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 960 μSTRAIN/SEC:
7 SPECIMENS

279 (1929)	273 (1887)	267 (1845)	218 (1503)
276 (1905)	272 (1880)	254 (1753)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 96 μSTRAIN/SEC:
10 SPECIMENS

301 (2081)	280 (1935)	261 (1805)	231 (1598)
292 (2014)	277 (1912)	259 (1790)	
291 (2010)	265 (1833)	234 (1616)	

APPENDIX B – (continued)

B. LAMINATE NO. 1 (100/0/0)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 71300 μSTRAIN/SEC:
10 SPECIMENS

-99 (-680)	-93 (-637)	-84 (-577)	-73 (-499)
-99 (-679)	-92 (-633)	-80 (-546)	
-97 (-667)	-91 (-625)	-77 (-526)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 7130 μSTRAIN/SEC:
7 SPECIMENS

-96 (-662)	-92 (-629)	-89 (-613)	-86 (-593)
-93 (-641)	-91 (-621)	-89 (-608)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 713 μSTRAIN/SEC:
7 SPECIMENS

-93 (-640)	-92 (-634)	-89 (-609)	-86 (-593)
-93 (-638)	-92 (-632)	-88 (-601)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 71 μSTRAIN/SEC:
10 SPECIMENS

-92 (-633)	-84 (-578)	-76 (-518)	-65 (-443)
-90 (-621)	-83 (-571)	-72 (-497)	
-88 (-601)	-83 (-569)	-71 (-487)	

APPENDIX B — (continued)

C. LAMINATE NO. 1 (100/0/0)

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 35000 μSTRAIN/SEC:
9 SPECIMENS

-89 (-613)	-60 (-410)	-55 (-377)
-66 (-451)	-58 (-397)	-48 (-327)
-63 (-431)	-56 (-381)	-44 (-300)

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 3500 μSTRAIN/SEC:
7 SPECIMENS

-54 (-371)	-53 (-361)	-51 (-346)	-45 (-308)
-54 (-369)	-52 (-354)	-49 (-336)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 350 μSTRAIN/SEC:
7 SPECIMENS

-54 (-373)	-50 (-345)	-48 (-328)	-41 (-280)
-53 (-364)	-49 (-332)	-43 (-294)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 35 μSTRAIN/SEC:
9 SPECIMENS

-48 (-330)	-46 (-313)	-42 (-285)
-47 (-319)	-45 (-305)	-41 (-279)
-46 (-318)	-44 (-303)	-40 (-270)

APPENDIX B – (continued)

D. LAMINATE NO. 2 (0/100/0)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 148000 μSTRAIN/SEC:
10 SPECIMENS

34 (237)	34 (234)	33 (232)	33 (228)
34 (235)	33 (233)	33 (230)	
34 (234)	33 (232)	33 (230)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 14800 μSTRAIN/SEC:
7 SPECIMENS

32 (226)	32 (225)	32 (222)	31 (218)
32 (225)	32 (223)	31 (220)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 1480 μSTRAIN/SEC:
7 SPECIMENS

31 (219)	31 (215)	31 (214)	30 (213)
31 (217)	31 (215)	31 (213)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 148 μSTRAIN/SEC:
10 SPECIMENS

30 (209)	30 (208)	30 (208)	29 (205)
30 (209)	30 (208)	30 (207)	
30 (208)	30 (208)	29 (205)	

APPENDIX B – (continued)

E. LAMINATE NO. 2 (0/100/0)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 96500 μSTRAIN/SEC:
10 SPECIMENS

-43 (-292)	-33 (-224)	-31 (-212)	-23 (-155)
-34 (-231)	-32 (-219)	-30 (-205)	
-33 (-228)	-32 (-218)	-30 (-201)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 9650 μSTRAIN/SEC:
7 SPECIMENS

-32 (-216)	-31 (-208)	-29 (-199)	-28 (-188)
-31 (-212)	-30 (-201)	-29 (-196)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 965 μSTRAIN/SEC:
7 SPECIMENS

-32 (-217)	-30 (-204)	-29 (-199)	-27 (-180)
-32 (-214)	-29 (-199)	-27 (-186)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 96 μSTRAIN/SEC:
10 SPECIMENS

-33 (-225)	-33 (-222)	-32 (-217)	-24 (-161)
-33 (-224)	-33 (-222)	-31 (-211)	
-33 (-223)	-32 (-220)	-29 (-198)	

APPENDIX B – (continued)

F. LAMINATE NO. 2 (0/100/0)

ETW TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 193000 μSTRAIN/SEC:
10 SPECIMENS

31 (213)	30 (209)	28 (196)	27 (186)
30 (213)	30 (208)	28 (195)	
30 (209)	28 (196)	28 (193)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 193 μSTRAIN/SEC:
10 SPECIMENS

30 (206)	29 (201)	28 (195)	27 (190)
29 (205)	28 (197)	28 (193)	
29 (203)	28 (195)	27 (191)	

G. LAMINATE NO. 2 (0/100/0)

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 77000 μSTRAIN/SEC:
9 SPECIMENS

-22 (-148)	-21 (-140)	-20 (-134)
-21 (-145)	-20 (-138)	-20 (-132)
-21 (-143)	-20 (-136)	-18 (-125)

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 77 μSTRAIN/SEC:
10 SPECIMENS

-17 (-114)	-16 (-111)	-16 (-105)	-15 (-99)
-17 (-112)	-16 (-109)	-15 (-104)	
-16 (-111)	-16 (-107)	-15 (-103)	

APPENDIX B – (continued)

H. LAMINATE NO. 3 (48/48/4)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 142000 μSTRAIN/SEC:
10 SPECIMENS

98 (677)	92 (637)	88 (606)	79 (545))
95 (659)	91 (629)	86 (598)	
93 (642)	90 (621)	85 (592)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 14200 μSTRAIN/SEC:
7 SPECIMENS

93 (647)	91 (631)	89 (615)	87 (599)
93 (644)	91 (629)	88 (609)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 1420 μSTRAIN/SEC:
7 SPECIMENS

94 (651)	88 (610)	87 (605)	85 (592)
89 (618)	88 (609)	86 (597)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 142 μSTRAIN/SEC:
10 SPECIMENS

98 (677)	92 (638)	89 (619)	86 (598)
94 (653)	92 (637)	89 (616)	
94 (649)	91 (630)	88 (607)	

APPENDIX B – (continued)

I. LAMINATE NO. 3 (48/48/4)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 65300 μSTRAIN/SEC:
10 SPECIMENS

-73 (-502)	-66 (-449)	-64 (-437)	-60 (-414)
-69 (-470)	-65 (-449)	-63 (-434)	
-68 (-463)	-65 (-445)	-62 (-427)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 6530 μSTRAIN/SEC:
7 SPECIMENS

-75 (-515)	-64 (-436)	-63 (-431)	-61 (-414)
-67 (-460)	-63 (-432)	-61 (-418)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 653 μSTRAIN/SEC:
7 SPECIMENS

-72 (-491)	-71 (-485)	-69 (-471)	-62 (-424)
-71 (-486)	-69 (-474)	-64 (-435)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 65 μSTRAIN/SEC:
10 SPECIMENS

-72 (-491)	-70 (-481)	-69 (-475)	-67 (-458)
-72 (-491)	-70 (-479)	-69 (-475)	
-71 (-484)	-69 (-475)	-68 (-468)	

APPENDIX B – (continued)

J. LAMINATE NO. 3 (48/48/4)

ETW TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 14400 μSTRAIN/SEC:
11 SPECIMENS

127 (875)	114 (790)	112 (774)	108 (750)
118 (819)	113 (781)	109 (754)	105 (723)
116 (803)	112 (777)	109 (752)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 144 μSTRAIN/SEC:
11 SPECIMENS

126 (871)	118 (817)	116 (800)	108 (749)
121 (834)	118 (816)	114 (792)	105 (728)
119 (823)	116 (800)	114 (789)	

K. LAMINATE NO. 3 (48/48/4)

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 43500 μSTRAIN/SEC:
11 SPECIMENS

-55 (-374)	-50 (-343)	-47 (-325)	-44 (-304)
-54 (-369)	-50 (-340)	-46 (-313)	-44 (-298)
-50 (-345)	-49 (-338)	-45 (-308)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 43 μSTRAIN/SEC:
11 SPECIMENS

-50 (-342)	-43 (-296)	-42 (-285)	-39 (-264)
-45 (-306)	-43 (-296)	-41 (-282)	-38 (-257)
-43 (-296)	-43 (-293)	-40 (-275)	

APPENDIX B – (continued)

L. LAMINATE NO. 4 (16/80/4)

RTD TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 214000 μSTRAIN/SEC:
10 SPECIMENS

56 (391)	51 (355)	50 (344)	49 (341)
53 (366)	51 (351)	49 (342)	
52 (363)	50 (346)	49 (342)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 21400 μSTRAIN/SEC:
7 SPECIMENS

54 (377)	52 (360)	50 (348)	48 (336)
52 (363)	51 (355)	49 (343)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 2140 μSTRAIN/SEC:
7 SPECIMENS

52 (359)	50 (346)	49 (342)	48 (332)
51 (351)	49 (342)	49 (341)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 214 μSTRAIN/SEC:
10 SPECIMENS

51 (354)	50 (348)	49 (343)	48 (330)
51 (351)	50 (346)	49 (340)	
50 (348)	50 (345)	49 (340)	

APPENDIX B – (continued)

M. LAMINATE NO. 4 (16/80/4)

RTD COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 98700 μSTRAIN/SEC:
10 SPECIMENS

-52 (-359)	-46 (-317)	-42 (-286)	-39 (-266)
-52 (-356)	-46 (-314)	-40 (-271)	
-49 (-332)	-43 (-292)	-39 (-268)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 9870 μSTRAIN/SEC:
7 SPECIMENS

-49 (-333)	-47 (-324)	-42 (-289)	-36 (-247)
-49 (-332)	-45 (-308)	-39 (-267)	

3) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 987 μSTRAIN/SEC:
7 SPECIMENS

-53 (-361)	-49 (-336)	-48 (-328)	-44 (-301)
-51 (-351)	-49 (-332)	-47 (-319)	

4) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 99 μSTRAIN/SEC:
10 SPECIMENS

-49 (-336)	-47 (-320)	-47 (-318)	-42 (-288)
-48 (-330)	-47 (-318)	-46 (-311)	
-48 (-330)	-47 (-318)	-44 (-303)	

APPENDIX B – (continued)

N. LAMINATE NO. 4 (16/80/4)

ETW TENSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 141000 μSTRAIN/SEC: 11 SPECIMENS

53 (370)	52 (363)	51 (352)	50 (348)
53 (367)	52 (360)	51 (352)	50 (346)
53 (366)	52 (359)	51 (352)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 141 μSTRAIN/SEC: 11 SPECIMENS

52 (360)	51 (353)	49 (341)	48 (333)
51 (357)	50 (348)	48 (335)	47 (329)
51 (355)	49 (341)	48 (333)	

O. LAMINATE NO. 4 (16/80/40

ETW COMPRESSION TEST

1) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 61500 μSTRAIN/SEC: 10 SPECIMENS

-35 (-236)	-34 (-229)	-32 (-216)	-27 (-183)
-34 (-231)	-32 (-220)	-31 (-209)	
-34 (-230)	-32 (-216)	-30 (-205)	

2) STRENGTH (KSI (MPa)) FOR STRAIN RATE = 61 μSTRAIN/SEC: 9 SPECIMENS

-28 (-191)	-27 (-185)	-27 (-180)
-28 (-189)	-27 (-184)	-26 (-178)
-27 (-187)	-27 (-182)	-25 (-170)

THIS PAGE INTENTIONALLY LEFT BLANK

Non-Government Agencies (continued)

	No. of Copies
University of Wyoming, Laramie, WY 82071 (Attn: Dr. D. Adams)	1
Villanova University, Villanova, PA 19085 (Attn: Dr. P. V. McLaughlin)	1
Virginia Polytechnic Institute, Blacksburg, VA 24061 (Attn: Dr. K. Reifsnider)	1
Vought Corporation, Dallas, TX 75265 (Attn: Mr. O. E. Dhonau/2-53442) (Attn: Dr. J. Renton)	1

	No. of Copies
McDonnell Douglas Corporation, St. Louis, MO 63166	
(Attn: Mr. J. Schier)	1
(Attn: Mr. C. Stenberg)	1
(Attn: Mr. R. Garrett	1
McDonnell Douglas Corporation, Long Beach, CA 90846	
(Attn: G. Lehman)	1
(Attn: D. Smillie)	1
Minnesota Mining and Manufacturing Company, St. Paul, MN 55104	
(Attn: Mr. W. Davis)	1
Northrop Aircraft Corporation, One Northrop Avenue, Hawthorne, CA 90250	
(Attn: Mr. L. Jeans)	1
(Attn: Mr. D. Stansbarger)	
(Attn: Mr. R. C. Isemann)	1
(Attn: Mr. R. M. Verette)	1
(Attn: Mr. B. Butler)	1
Owens Corning Fiberglass, Granville, OH 43023	
(Attn: Mr. D. Mettes)	1
Prototype Development Associates, Inc., 1560 Brookhollow Drive, Santa Ana, CA 92705	
(Attn: E. L. Stanton)	1
Rockwell International, Columbus, OH 43216	
(Attn: Mr. F. Kaufman)	1
(Attn: Mr. M. Schweiger)	1
Rockwell International, Los Angeles, CA 90009	
(Attn: Dr. Lackman)	1
Rockwell International, Tulsa, OK 74151	
(Attn: Mr. E. Sanders)	
(Attn: Mr. J. H. Powell)	1
Rohr Corporation, Riverside, CA 92503	
(Attn: Dr. F. Riel)	1
(Attn: Mr. R. Elkin)	1
School of Engineering and Applied Science, Materials Research Laboratory, Washington University, Campus Box 1087, St. Louis, MO 63130	
(Attn: T. Hahn)	1
Sikorsky Aircraft, Stratford, CT 06622	
(Attn: Mr. J. Ray)	1
Teledyne Ryan Aeronautical Company, San Diego, CA 92138	
(Attn: Mr. R. Long)	1
Union Carbide Corporation, Cleveland, OH 44101	
(Attn: Dr. H. F. Volk)	1
University of Dayton Research Institute, 300 College Park Ave., Dayton, OH 45469	
(Attn: Dr. J. Gallagher)	1
University of Delaware, Mechanics & Aerospace Eng. Dept., Evans Hall, Newark, DE 19711	
(Attn: Dr. R. B. Pipes)	1
University of Oklahoma, Norman, OK 73019	
(Attn: Dr. C. W. Bert, School of AMNE)	1

Non-Government Activities (continued)

	No. of Copies
Drexel University, Phila., PA 19104	
(Attn: Dr. P. C. Chou)	1
(Attn: Dr. A. S. D. Wang)	1
Effects Technology, Inc., 5383 Hollister Avenue, P.O. Box 30400, Santa Barbara, CA 93111 (Attn: Robert Globus)	1
E. I. DuPont Company, Wilmington, DE 19898	
(Attn: Dr. J. Pigoiacampi)	1
Fairchild Republic Company, Farmingdale, L. I., NY 11735	
(Attn: Mr. Frank Costa)	1
Georgia Institute of Technology, Atlanta, GA	
(Attn: Prof. W. H. Horton)	
General Dynamics/Convair, San Diego, CA 92138	
(Attn: Mr. D. R. Dunbar)	1
(Attn: Mr. W. G. Scheck)	1
General Dynamics, Fort Worth, TX 76101	
(Attn: Mr. J. A. Fant)	1
(Attn: Dr. D. Wilkins (Composite Structures Eng. Dept.)	1
General Electric Company, Phila., PA 19101	
(Attn: Dr. C. Zweben)	1
(Attn: Mr. A. Garber)	1
Great Lakes Carbon Corporation, NY, New York 10017	
(Attn: Mr. W. R. Benn, Mgr., Market Development)	1
Gruuman Aerospace Corporation, South Oyster Bay Rd., Bethpage, Long Island, NY 11714	
(Attn: Mr. R. Hadcock)	1
(Attn: Mr. S. Dastin)	1
Hercules Aerospace Division, P.O. Box 210, Cumberland, MD 21502	
(Attn: Mr. D. Hug)	1
HITCO, 1600 West 135th Street, Gardena, CA 90249	
(Attn: Mr. N. Myers)	1
ITT Research Institute, Chicago, IL 60616	
(Attn: Mr. K. Hofar)	1
J. P. Stevens & Co., Inc., New York, NY 10036	
(Attn: Mr. H. I. Shulock)	1
Kaman Aircraft Corporation, Bloomfield, CT 06002	
(Attn: Technical Library)	1
Lehigh University, Bethlehem, PA 18015	
(Attn: Dr. G. C. Sih)	1
Lockheed-California Co., Burbank, CA 91520	
(Attn: Mr. E. K. Walker)	1
(Attn: Mr. Vaughn)	1
(Attn: Mr. A. James)	1
Lockheed-California Co., Rye Canyon Research Lab, Burbank, CA 91520	
(Attn: Mr. Don E. Pettit)	1
Lockheed-Georgia Company, Marietta, GA 30063	
(Attn: Technical Information Dept., Dept. 72-34, Zone 26)	1
Materials Sciences Corporation, Spring House, PA 19477	1
Philadelphia College of Textiles and Science, School House Lane and Henry Ave., Philadelphia, PA 19144 (Attn: Dr. Frank Ko)	1

Government Activities (continued)

	No. of Copies
NAVSHIPRANDCEN, Annapolis, MD 21402 (Attn: Code 2870, Mr. H. Edelstein)	1
NAVAL SURFACE WEAPONS CENTER, White Oak Laboratory, Silver Spring, MD 20910 (Attn: Dr. J. Goff, Materials Evaluation Branch (R-34)	1
NOL, White Oak, MD 20910 (Attn: Mr. F. R. Barnet)	1
NRL, Washington, D.C. 20375 (Attn: Dr. I. Wolock)	1
ONR, Washington, D.C. 20362 (Attn: Dr. N. Perrone)	1
PLASTEC, Picatinny Arsenal, Dover, NJ 07801 (Attn: Mr. H. Pebly)	1
(Attn: Librarian, Code DRDAR-SCM-0, Bldg. 351-N	
U.S. Army Materials and Mechanics Research Center (DRXMR-PL) Watertown, MA 02172 (Attn: Dr. E. Lenoe)	1
(Attn: Mr. D. Oplinger)	1
U.S. Army Research Office, Durham, NC 27701	1
U.S. Army R&T Lab (AVRADCOM), Ames Research Center, Moffett Field, CA 94035 (Attn: Mr. F. Immen, DAVDL-AS-M.S. 207-5, Dr. R. Foye)	2
David Taylor Naval Ship Research & Development Center, Code 2822, Annapolis, MD 21402 (Attn: Mr. A. Macander, Mr. R. Crane)	2

Non-Government Activities

Avco, Aero Structures Division, Nashville, TN 37210	1
Battelle Columbus Laboratories, Metals and Ceramics Information Center, 505 King Avenue, Columbus, OH 43201	1
Bell Aerospace Company, Buffalo, NY 14240 (Attn: Zone I-85, Mr. F. M. Anthony)	1
Bell Helicopter Company, Fort Worth, TX 76101 (Attn: Mr. G. Reis Alsmiller, Jr.)	1
Bendix Products Aerospace Division, South Bend, IN 46619 (Attn: Mr. R. V. Cervelli)	1
Boeing Company, P.O. Box 3707, Seattle, WA 98124 (Attn: Mr. R. E. Horton, ms 9K-23)	1
(Attn: Dr. R. June)	1
Boeing Company, Vertol Division, P.O. Box 16858, Philadelphia, PA 19142 (Attn: Mr. R. L. Pinckney)	1
(Attn: Mr. D. Hoffstedt)	1
(Attn: Mr. L. Marchinski)	1
Boeing Company, Wichita, KS 67210 (Attn: R. D. Hoaglanb – M. S. - K32-95)	1
Cabot Corporation, Billerica Research Center, Billerica, MA 01821	1
Compositek Engineering Corporation, 6925-1 Aragon Circle, Buena Park, CA 90620 (Attn: J. V. Noyes)	1

LMED

8