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FATIGUE BEHAVIOR OF GRAPHITE COMPOSITES

Final Report
(9 Feb. 1971 to 8 Feb. 1972)

February, 1972

by

P. N. Rao
K. E. Hofer, Jr.

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13. ABSTRACT

The work reported consists of two phases of investigation aimed at improving the material behavior of a graphite/epoxy prepreg composite with particular relevence to its fatigue performance.

(1) The first phase deals with the improvement of Modmor II/Narmco 5206 composite fatigue strength and its resistance to fatigue damage by interleaving the composite prepreg laminate with glass scrim cloth. Cantilever beam specimens of two fiber orientations were tested under uniform stress fatigue and sequential block fatigue loading.

(2) The second phase consists of flexural strength studies investigating the effects of ambient aging of Modmor II/Narmco 5206 prepreg composites on their elevated temperature properties. Aging has serious implications for the designer in that it would affect all aspects of material performance including fatigue. Besides ambient aging the investigation also included accelerated aging tests on laminates of two different fiber orientations with and without interleaving of scrim cloth.

In both phases of this investigation, the addition of glass scrim cloth contributes to an improvement in the mechanical behavior of graphite/epoxy prepreg composite.

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FOREWORD

This is the final report of IIT Research Institute Project No. D6060 titled, "Fatigue Behavior of Graphite Composites" conducted during the period from February 9, 1971 through February 8, 1972 for the Naval Air Systems Command, United States Department of the Navy under contract No. N-00019-71-C-0212. Mr. Max Stander (AIR 52032D) was the program monitor on behalf of the Naval Air Systems Command.

The program was conducted in the Mechanics of Materials Division of IIT Research Institute, Chicago, Illinois. Mr. P. N. Rao and Mr. K. E. Hofer, Jr. were Project Engineer and Project Manager respectively. The personnel who substantially contributed to the work reported herein are: Messrs. L. C. Bennett, K. E. Hofer, Jr., H. Lane, and P. N. Rao.

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FATIGUE BEHAVIOR OF GRAPHITE/EPOXY COMPOSITES

1.0 INTRODUCTION

The importance of fatigue behavior of materials is appreciated by todays' designer as it is this behavior that often restricts the material use and application. This is particularly true in the case of composite laminate materials because of their non-homogenous and anisotropic nature which leads to a potential for less familiar, but certainly just as serious fatigue damage mechanisms than other more conventional materials. Some of these less familiar vulnerabilities of the laminates include separation at interlaminar surfaces and debonding at fiber-matrix interfaces. Both mechanisms are accentuated by hostile environments such as humidity or temperature.

Graphite fiber/epoxy composites occupy an important place in the current overall picture of composite materials. Improvement of fatigue performance of graphite epoxy composites, then, is also important particularly where such improvements can be attained through material alterations. In this study an improvement in fatigue performance for the graphite composites under both sinusoidal loading as well as programmed sequential block fatigue loading was sought. The method to accomplish this improvement involved the interleaving of glass scrim cloth between consecutive layers of graphite prepreg. The governing philosophy for this expectation and previous experience at IITRI are discussed in an appropriate section.

Two fiber orientations were included in the study: one a simple laminate (45°/135°) and another more complex pseudoisotropic laminate (0°/± 45°/90°). The purpose of the first laminate was to determine the maximum extent of achievable improvement due to inclusion of glass scrim cloth in the composite.

The measure of improvement was judged by the increase in static strength and fatigue life of the composite and the resistance to composite damage as determined by microscopic observation of crack growth. The specimen configuration chosen was a cantilever beam with a span depth ratio of approximately 5. Under loading, this specimen is subjected to a state of complex stresses that include vertical and horizontal shear, tension and compression. The predominent damaging stresses are the tensile stress which is a maximum in the extreme outer fiber (or plies) of the beam that causes inter-tow cracking and the horizontal (interlaminar) shear stress with a maximum in the central plies of the composite that causes laminar separation. Although these two act simultaneously the damage is predominantly caused by tension stresses, through the initiation and progress of inter-tow cracks. This is as it should be since the ratio of maximum bending stresses to maximum horizontal shear stress is given by:

$$\frac{\text{Max. Bending Stress}}{\text{Max. Hor. Shear Stress}} = \frac{6PL}{wt^2} \Big/ \frac{3P}{2wt} = 2/t$$

which is of the order of 15 for the specimen dimensions adopted. Compared to this, the ratio of the respective failure stresses is in the range of 5 to 6. From the static test data which will be presented in Section 3 of this report, it will be shown that the maximum bending stresses (calculated) are close to the flexural strength of the particular composite whereas the calculated max. horizontal shear stresses are below their interlaminar shear strength.

For microscopic observation of crack initiation and growth the cantilever beam specimen has been demonstrated to be ideal. The cantilever beam specimens have also been used by other investigators[1] for studying fatigue properties which make it possible to compare the test results.

The polished specimen sections taken at an appropriate location (beam support) provided visual evidence of damage such as cracking, debonding of fibers from matrix, and laminar separation. In addition to this qualitative information, the tests produced quantitative crack growth data (percent of maximum penetrable number of laminae) as a function of the number of fatigue stress cycles or sequential blocks of fatigue loading.

The fatigue performance of composite laminates, are severely affected by hostile moisture environments. Thus, a portion of this study was devoted to an investigation of adverse effects of moisture on the elevated temperature performance of graphite/epoxy composites. To date, little reliable data on the recently discovered adverse effects of composite aging under ambient conditions particularly on its elevated temperature properties was available. Furthermore, since the fatigue process itself is a time related process, composite aging would add complexity to the problem of analyzing fatigue results obtained in moisture environments. Thus as a first step, the elevated temperature static strength reduction of graphite/epoxy composites due to ambient aging was determined. Two fiber orientations namely a cross ply (0°/90°) laminate and a pseudoisotropic configuration (0°/± 45°/90°) were employed. Ambient aging was studied using flexural test methods. This selection was based on the hypothesis that aging influenced the matrix and fiber/matrix interface performance. Flexural tests would be affected by both these factors to a somewhat greater degree than tensile properties. Similar to the fatigue studies, glass scrim cloth was included as an element of possible improvement in composite behavior.

Table I summarizes the program activity conducted.

Table I

PROGRAM PLAN

Task Description	Number of Specimens			
	Modmor II/Narmco 5206		Modmor II/Scrim Cloth/ Narmco 5206	
	Cant. Beam 16 ply, Pseudo-Isotropic	Cant. Beam 16 Ply, 45°, 135°	Cant. Beam 16 ply, Pseudo-Isotropic	Cant. Beam 16 Ply, 45°, 135°
I. FATIGUE STUDIES				
Static Tests	5	5	5	5
Fatigue Tests (R = 0.1), S-N Curve Data Generation	10	10	10	10
Fatigue Run-out tests (R = 0.1), Specimens sectioned & polished for Microscopic Inspection	15	25	15	25
Spectrum Fatigue (R = 0.1) tests and Microscopic Inspection	-	10	-	10
Total	30	50	30	50
	16 ply, Pseudo-Isotropic Flexure Beam	16 ply, 0° - 90° Flexure Beam	16 ply, Pseudo-Isotropic Flexure Beam	16 ply, 0° - 90° Flexure Beam
II. AGING STUDIES				
Control Tests - Immediately after specimen fabrication, single point loaded beam tests at R.T. and elevated temperatures	30	30	30	30
Aging Tests - Exposed to 98% R.H. and 120°F for 5 weeks, single point loaded beam tests at R.T. and elevated temperatures	15	15	15	15
Total	45	45	45	45

2.0 MATERIAL PROCUREMENT AND SPECIMEN FABRICATION

Modmor II graphite fiber preimpregnated with Narmco 5206 resin was selected for study in this program. Prepreg material in the form of yard length 12 inches wide broadgoods were obtained from Whittaker Corporation, Narmco R & D Division, San Diego, California.

2.1 Material Procurement

The material was procured to McDonnell-Douglas Specifications DMS-1936 B class 2. It was supplied in meter length broadgoods and was characterized by Whittaker Corporation as shown in Tables II and III. The material was stored at 0°F in a freezer until the start of the lay-up operations.

2.2 Specimen Fabrication

The 16 ply composite plates for 5 in. x ½ in. flexural specimens used in the aging studies consisted of two orientations:

1. $(0°/90°)_{8t}$ Orthogonal lay-up (Refer to Fig. 1-a)
2. $(0°/\pm 45°/90°)_{4t}$ Pseudoisotropic lay-up (Refer to Fig. 1-b).

For the Fatigue studies in which 16 ply, 2 in. x 3/4 in. cantilever beam specimens were employed, the orientations are:

1. $(+45°/-45°)_{8t}$ or $(45°/135°)_{8t}$ (Refer to Fig. 1-c)
2. $(0°/\pm 45°/90°)_{4t}$ (Refer to Fig. 1-b)

These laminates will be mentioned elsewhere in the report without the subscripts as shown in Fig. 1.

The green lay-up was prepared by stacking the required number of sheets in the appropriate directions to provide 12 inch wide plates of different lengths depending on the number of speci-

TABLE II

WHITTAKER CORPORATION CERTIFICATION OF MODMOR II/NARMCO 5206 PREPREG GRAPHITE MATERIAL

MATERIAL	Modmor II/5206
FIBER	Modmor II Meter
FIBER BATCH NO.	H-1159
TOWS PER INCH	5
RESIN	1004 batch 27
RESIN % BY WTS.	44.8
LOT NO.	0079
MFG. DATE	16 April 1971
SHEET SIZE	12" x 38"
NO. SHEETS	27
TOTAL WT. PREPREG	6.06 lbs.

TABLE III

WHITTAKER CORPORATION CERTIFICATION OF MODMOR II/NARMCO 5206 PREPREG GRAPHITE MATERIAL

MATERIAL	Modmor II/5206
FIBER	Modmor II Meter
FIBER BATCH NO.	H 1159
TOWS PER INCH	5
RESIN	1004 batch 27
RESIN % BY WEIGHT	43.2%
LOT NO.	0083
MANUFACTURING DATE	20 May 1971
SHEET SIZE	12" x 38"
NO. SHEETS	9
TOTAL WT. OF PREPREG	1.964 lbs.

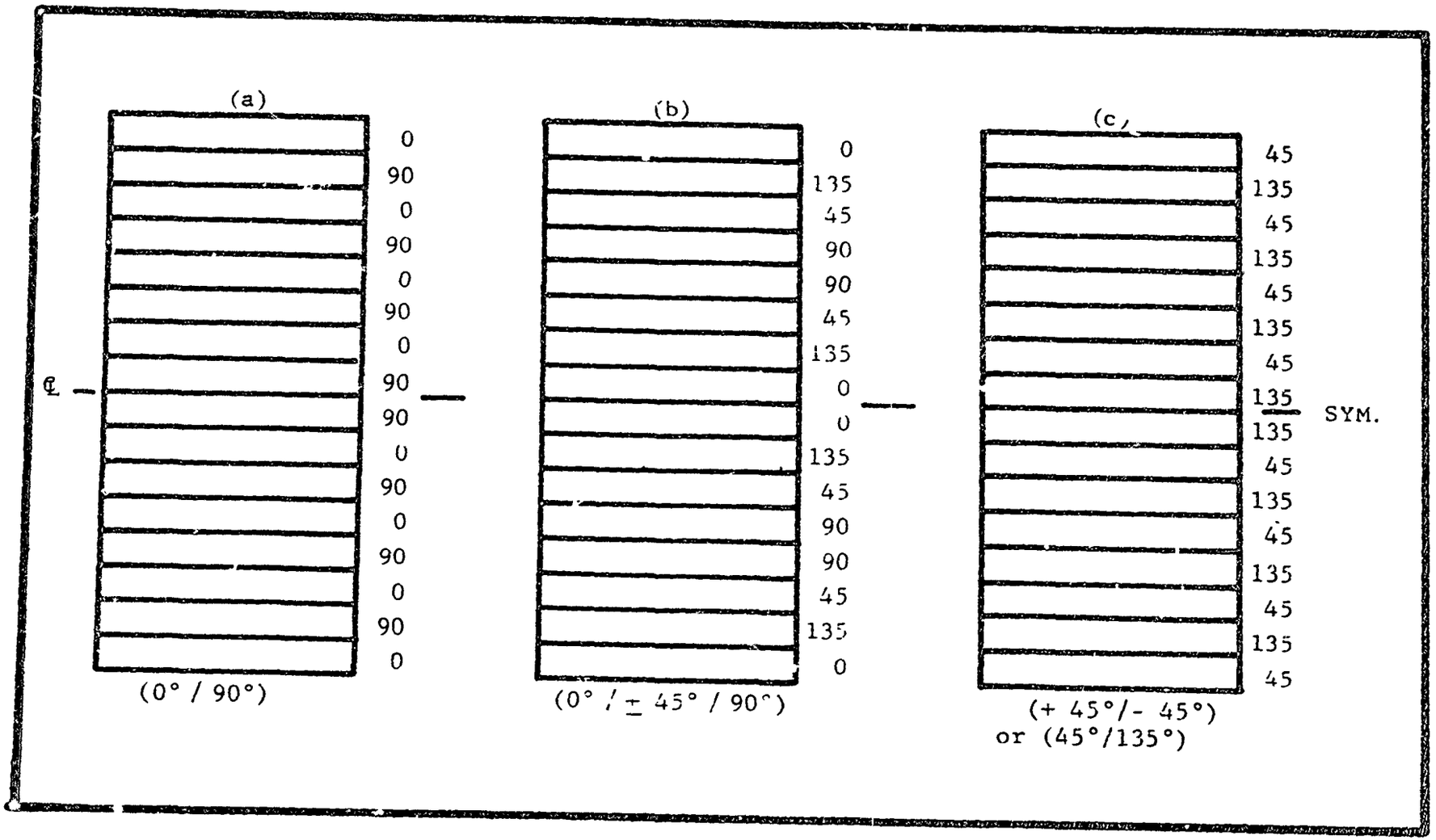


FIG. 1. ORIENTATION DETAILS OF MODMOR II/NARMCO 5206 PREPREG LAY-UP.

mens required in each category. Where the scrim cloth (104-20 x 20 glass cloth) was employed, it was interleaved between consecutive layers of the graphite prepreg material. The green lay-up was subsequently covered with two bleed cloth layers and finally with a teflon coated glass cloth. Before placing the lay-up in the autoclave, a barrier dam was placed surrounding the whole package to provide the vacuum environment. The cure cycle followed was according to the following schedule:

1. Vacuum of 14.7 psi applied to the bag
2. Temperature increased to 275°F and held constant for one hour
3. Pressure of 100 psi applied to the autoclave
4. Temperature increased to 350°F and held constant for two hours
5. Post curing for two hours at 400°F.

The composite plate was then cut to provide the required test specimens.

3.0 FATIGUE DAMAGE STUDIES

An understanding of the nature and progress of the cracking which takes place in a composite material as a result of repeated stress cycling will eventually lead to methods of alleviating composite fatigue degradation. The nature of the cracking process is best understood by visual observation, i.e. via microscopic examination of cross sections of typical composites subjected to repeated stress cycling but which were interrupted prior to complete failure of the laminate. It was the purpose of this portion of the program to select a composite material, to fabricate specimens and to subject them to repeated stress cycling followed by just such microscopic examination.

Modmor II graphite/Narmco 5206 epoxy prepreg material was selected for these studies because of its current potential for application in advanced aerospace technology. Previous studies[2/] have shown that the interleaving of 102 glass scrim cloth between plies of this material substantially upgraded its fatigue resistance. Several fiber orientations were considered for the study. A pseudoisotropic (0°/90°/± 45°) laminate and a (45°/135°) laminate, each with 16 (sixteen) plies and both with and without scrim cloth were selected.

The test specimen used was a cantilever beam 2 in. long x 0.75 in wide. Such a specimen under a concentrated load at the free end is subject to a state of stress containing tension, compression and shear components depending on the location of the element in the beam. Fig. 2 is a schematic which shows the specimen dimensions and the method of loading, both statically and dynamically. For a beam loaded as shown in Fig. 2 the interlaminar shear stresses are given by:

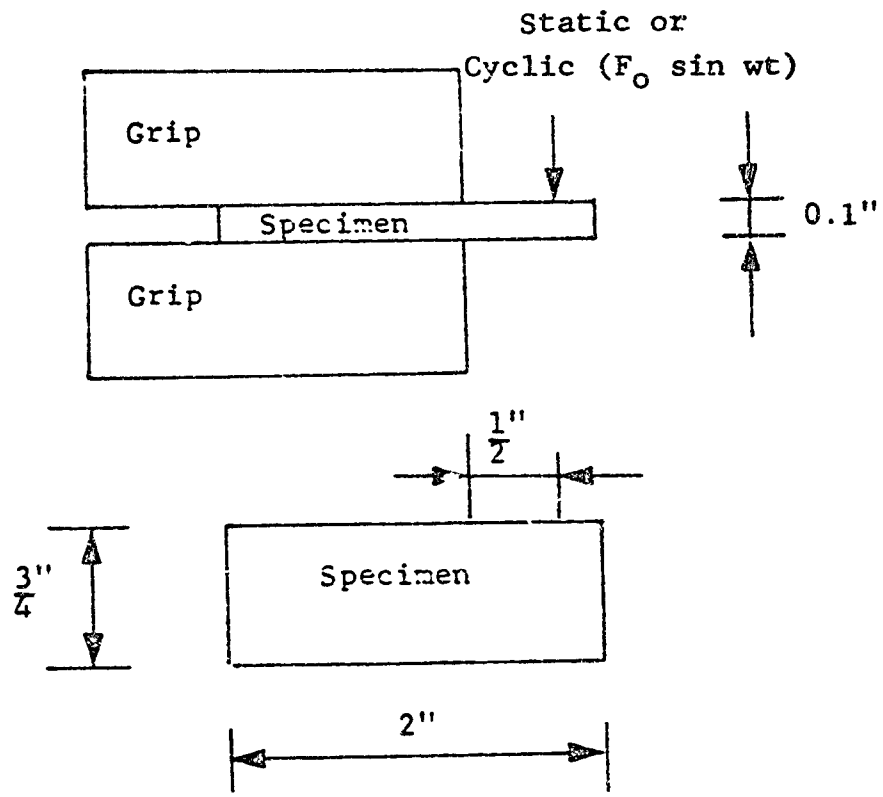


FIG. 2 CANTILEVER BEAM SPECIMENS AND METHOD OF LOADING

$$\tau = 3P/2wt$$

where τ = interlaminar shear stress, psi

P = load, lbs.

w = width, in.

t = thickness, in.

and the bending stresses are given by:

$$\sigma_t = \frac{6PL}{wt^2}, \quad \sigma_c = -\frac{6PL}{wt^2}$$

where σ_t = tensile stress in outer fibers of beam, psi

σ_c = compressive stress in outer fibers of beam, psi

L = length of cantilever beam, in.

and P, w, t are as defined above.

For a beam of the dimensions selected $\sigma_t/\tau = 15$ while σ_t, ult/τ ult = 5.

Thus, the most likely mode of failure statically would be tensile. Under repeated stress cycling, tension fatigue (R=0.1) results would be most likely to represent the type of failures occuring in the cantilever beam. The exact mode of failure would be modified to a great extent by the presence of shear stresses in the beam which could redirect or ultimately control the progress and rate of crack growth. Since glass scrim cloth provides a certain measure of shear resistance, it was possible that substantial gains in fatigue performance would accrue as a result of employing it in the composites. Thus, specimens with and without glass cloth interlayers were employed in this study so that this possibility could be substantiated.

Baseline static data was first obtained on the two laminate types, both with and without scrim cloth interlayers. Pseudoisotropic laminate static data is shown in Tables IV and V for both conventional and interlayer constructions respectively. Similarily, tables VI and VII present the results for the (45°/135°) laminates. A study of these results indicates a twenty percent increase in the bending strength capability of pseudoisotropic material as a result of scrim cloth additions (from 71.8 ksi, no scrim cloth interlayers to 86.0 ksi with scrim cloth interlayers). Practically no increase was shown for static bending strength capabilities (2% increase from 72.4 ksi to 73.8 ksi) for (45°/135°) laminates. In the ± 45° laminates, the failure is governed principally by in-plane shear stresses and the individual cracks arise largely in the planes normal to the scrim cloth interlayers.

3.2 Fatigue Behavior of Modmor II/5206 Composites

Fatigue life (S-N) behavior of the graphite composites was obtained for the 16 ply cantilever beam specimens by testing the specimens at R=0.1 (Room temperature and Dry Conditions). From these curves appropriate load levels were selected for subjecting the specimens to stress cycling for various percentages of the average cyclic life at that given stress for microscopic studies. In addition the appropriate load levels for programmed sequential block loadings were established from the P-N curves. A summary of this data is shown in the various tables and figures listed below:

Fiber Orientation	Table No.	Figure No.
(0°,± 45°, 90°)	VIII	3
(0°,± 45°, 90°) (w/scrim cloth)	IX	
(45°/135°)	X	4
(45°/135°) (w/scrim cloth)	XI	

TABLE IV

STATIC TEST RESULTS OF MODMOR II/NARMCO 5206
PREPREG 16 PLY (0°/± 45°/90°) COMPOSITE CANTILEVER BEAM
SPECIMENS TESTED TO FAILURE AT ROOM
TEMPERATURE DRY CONDITIONS

Specimen Number	Width (in.)	Thickness (in.)	Ultimate Load (lbs)	Calculated Interlaminar Shear Stress (ksi)	Calculated Bending Stress * (ksi)
A1-3	0.755	0.128	280	4.4	67.9
A1-9	0.759	0.130	334	5.1	78.1
A1-12	0.760	0.134	316	4.6	69.4
	AVERAGE		310	4.7	71.8

* Average flexural strength = 78.9 ksi (Section 4)

TABLE V

STATIC TEST RESULTS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY (0°/± 45°/90°) COMPOSITE CANTILEVER BEAM SPECIMENS (WITH SCRIM CLOTH) TESTED TO FAILURE AT ROOM TEMPERATURE DRY CONDITIONS

Specimen Number	Width (in.)	Thickness (in.)	Ultimate Load (lbs)	Calculated Interlaminar Shear Stress (ksi)	Calculated Bending Stress * (ksi)
C2-4	0.760	0.130	386	5.8	90.2
C2-6	0.763	0.136	386	5.6	82.1
C2-8	0.756	0.139	417	6.1	85.6
	AVERAGE		396	5.8	86.0

* Average flexural strength = 80.9 (Section 4)

TABLE VI

STATIC TEST RESULTS OF MODMOR II/NARMCO 5206
PREPREG 16 PLY (45°/135°) COMPOSITE CANTILEVER BEAM
SPECIMENS TESTED TO FAILURE AT ROOM
TEMPERATURE DRY CONDITIONS

Specimen Number	Width (in.)	Thickness (in.)	Ultimate Load (lbs)	Calculated Interlaminar Shear Stress (ksi)	Calculated Bending Stress (ksi)
B3-4	0.756	0.121	261	4.3	70.7
B3-13	0.755	0.120	283	4.6	78.1
B3-28	0.764	0.118	259	4.3	73.0
B3-32	0.777	0.117	234	3.9	66.0
B3-46	0.766	0.117	260	4.4	74.4
	AVERAGE		259	4.3	72.4

TABLE VII

STATIC TEST RESULTS OF MODMOR II/NARMCO 5206
PREPREG 16 PLY (45°/135°) COMPOSITE CANTILEVER BEAM
SPECIMENS (WITH SCRIM CLOTH) TESTED TO FAILURE AT ROOM
TEMPERATURE DRY CONDITIONS

Specimen Number	Width (in.)	Thickness (in.)	Ultimate Load (lbs)	Calculated Interlaminar Shear Stress (ksi)	Calculated Bending Stress (ksi)
D-7	0.750	0.126	299	4.7	75.3
D-16	0.746	0.130	323	5.0	76.9
D-15	0.746	0.127	250	4.0	62.3
D-30	0.750	0.124	285	4.6	74.1
D-63	0.750	0.128	330	5.1	80.6
	AVERAGE		297	4.7	73.8

TABLE VIII

SUMMARY OF FATIGUE RESULTS FOR MODMOR II/NARMCO 5206
PREPREG 16 PLY (0°/ ± 45°/90°) COMPOSITE CANTILEVER BEAM
TESTS AT R = 0.1, ROOM TEMPERATURE DRY CONDITIONS

Specimen No.	Max. Load Applied/ Cycle (lbs)	Max. Calculated Shear Stress Applied/Cycle (ksi)	Max. Calculated Bending Stress Applied/Cycle (ksi)	Cycles to Failure (Cycles)
1-1	226	3.5	54.7	16,000
1-4	195	3.0	46.6	1.194×10^6
1-7	243	3.8	61.3	11,000
1-8	204	3.3	53.6	54,000
1-10	208	3.3	53.1	4,000
1-11	223	3.4	52.4	557,000
1-14	225	3.4	52.3	21,000

TABLE IX

SUMMARY OF FATIGUE RESULTS FOR MODMOR II/NARMCO 5206
PREPREC 16 PLY (0°/± 45°/90°) COMPOSITE (WITH SCRIM CLOTH)
CANTILEVER BEAM TESTS AT R=0.1, ROOM TEMPERATURE DRY CONDITIONS

Specimen Number	Max. Load Applied/ Cycle (lbs)	Max. Calculated Shear Stress Applied/Cycle (ksi)	Max. Calculated Bending Stress Applied/Cycle (ksi)	Cycles to Failure (Cycles)
2-1	308	5.0	67.4	2,000
2-2	282	4.5	58.9	19,000
2-3	289	4.0	55.9	16,000
2-5	243	3.5	51.0	15,000
2-7	211	3.0	44.8	1.9×10^6 ⊛
2-9	242	3.5	41.4	112,000

⊛ No failure, cycles run out.

TABLE X

SUMMARY OF FATIGUE RESULTS FOR MODMOR II/NARMCO 5206 PREPREG 16 PLY (45°/135°) COMPOSITE CANTILEVER BEAM TESTS AT R = 0.1, ROOM TEMPERATURE DRY CONDITIONS

Specimen Number	Max. Load Applied/ Cycle (lbs)	Max. Calculated Shear Stress Applied/Cycle (ksi)	Max. Calculated Bending Stress Applied/Cycle (ksi)	Cycles to Failure (Cycles)
B3-5	118	2.0	34.8	2.09×10^6 ⊛
B3-6	187	3.0	49.0	38,000
B3-17	182	3.0	49.9	111,000
B3-21	148	2.5	42.9	1,000
B3-22	155	2.5	41.1	331,000
B3-23	165	2.7	44.7	12,000
B3-41	139	2.3	39.1	7.54×10^6 *
B3-42	204	3.3	55.0	8,000
B3-54	162	2.7	45.7	28,000
B3-55	167	2.8	47.9	76,000
B3-56	174	2.8	47.4	35,000

⊛ No failures, cycles run out

TABLE XI

SUMMARY OF FATIGUE RESULTS FOR MODMOR II/NARMCO 5206
PREPREG 16 PLY (45°/135°) COMPOSITE (WITH SCRIM CLOTH)
CANTILEVER BEAM TESTS AT R=0.1, ROOM TEMPERATURE DRY CONDITIONS

Specimen Number	Max. Load Applied/ Cycle (lbs)	Max. Calculated Shear Stress Applied/Cycle (ksi)	Max. Calculated Bending Stress Applied/Cycle (ksi)	Cycles to Failure (Cycles)
D4-19	187	3.0	48.0	112,000
D4-23	188	3.0	47.5	243,000
D4-36	218	3.4	53.2	5,000
D4-39	218	3.4	53.3	2,000
D4-42	145	2.3	36.5	2.33×10^6 *
D4-54	163	2.5	38.6	7.32×10^6
D4-58	174	2.8	45.3	62,000
D4-62	176	2.7	41.6	847,000
D4-56	206	3.2	50.3	4,000
D4-61	206	3.2	48.8	23,000
D4-25	178	2.8	43.6	29,000
D4-53	167	2.8	45.7	63,000
D4-40	176	2.8	44.5	75,000
D4-21	175	2.8	448	35,000

* No failure, cycles run out.

An examination of Figs. 3 and 4 demonstrates that scrim cloth interlayers improve the fatigue lives of the pseudoisotropic composites. The effect of scrim cloth interlayers on the fatigue of (45°/135°) composites is not as clear.

3.3 Fatigue Stress Cycling and Crack Development in Modmor II/ Narmco 5206 Composites

From the fatigue life data generated the following load levels were selected for stress cycling and crack progress investigations:

Fiber Orientations	Max. Load/ Cycle (lbs)	Calculated Max. Shear Stress/Cycle (ksi)	Calculated Max. Bending Stress/Cycle (ksi)
(0°/± 45°/90°)	185	3.5	65.4
(0°/± 45°/90°) (w/scrim cloth	210	3.5	58.3
(45°/135°)	168	2.8	47.1
(45°/135°) (w/scrim cloth)	174	2.8	45.2

Tables XII through XV present a schedule of the photomicrography showing specimen numbers, number of cycles that the particular specimen was subjected to a figure number for the photomicrograph of the specimen cross sections (presented in Appendix "A" at the end of this report). The cross sections were taken near the point of support of the cantilever beam specimens. At these sections, the crack development is greatest because the maximum bending moments occur at this location. The magnification of these photomicrographs is 20 x and the full depth of the specimens is shown.

Fig. 5 is a microphotograph showing typical crack development in a longitudinal section of a (45°/135°) cantilever beam specimen failed statically. The cracking initiated at the point

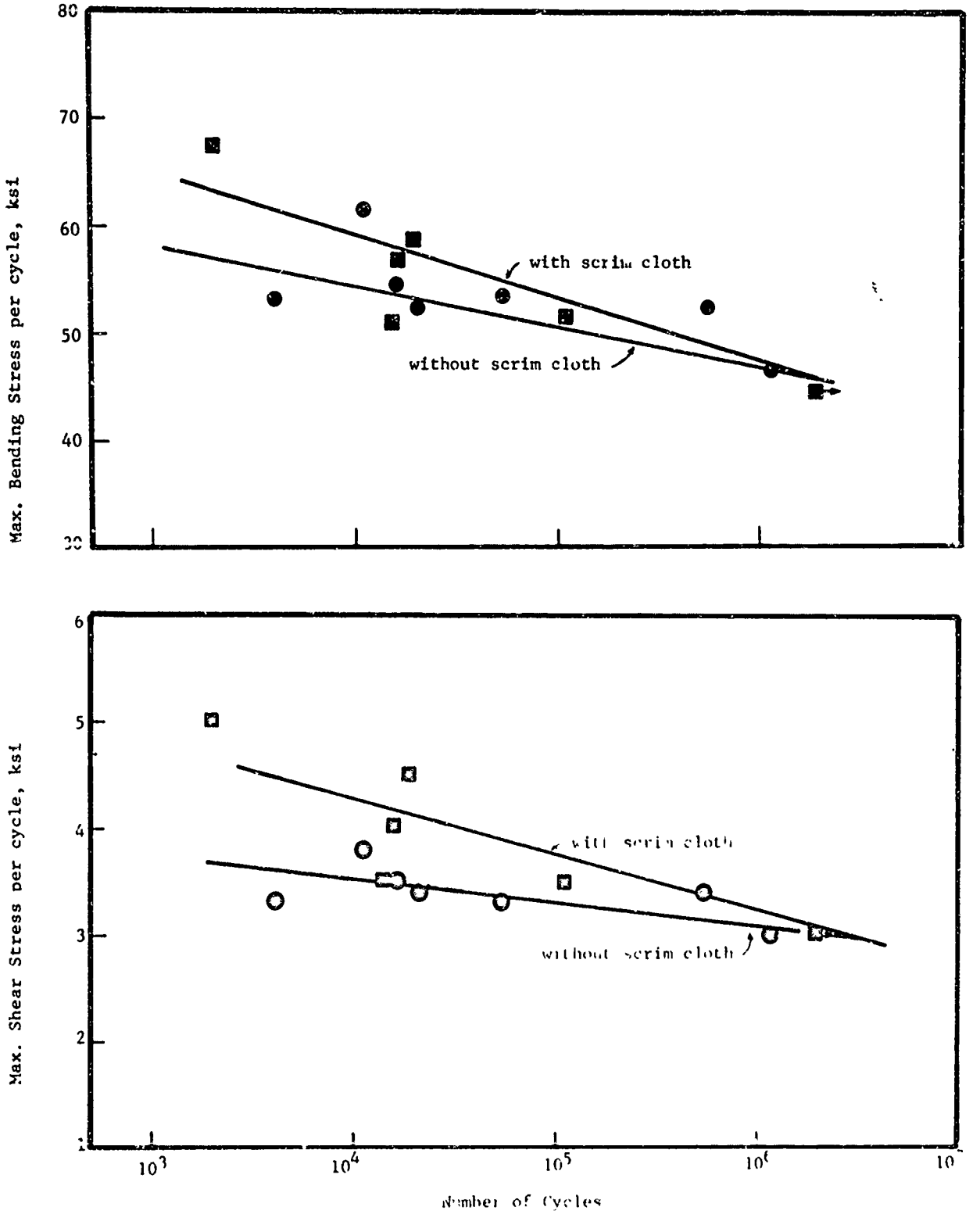


FIG. 3 SUMMARY OF FATIGUE RESULTS FOR MODMOR II/NARMCO 5206 PREPREG 16 PLY (0°/± 45°/90°) COMPOSITE CANTILEVER BEAM TESTS AT R = 0.1, ROOM TEMPERATURE DRY CONDITIONS

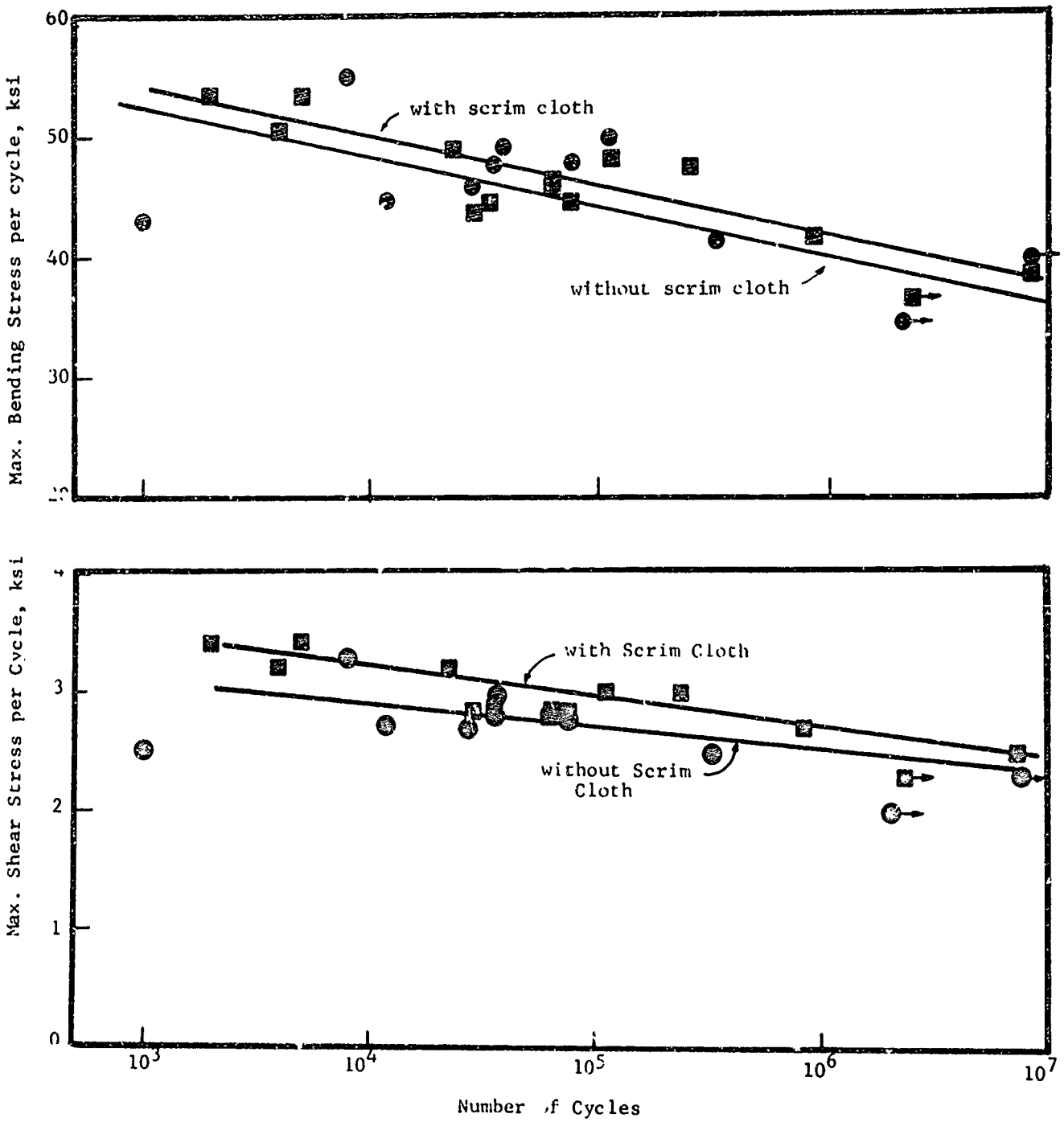


FIG. 4 SUMMARY OF FATIGUE RESULTS FOR MODMOR II/NARMCO 5206 PREPREG 16 PLY (45°/135°) COMPOSITE CANTILEVER BEAM TESTS AT R = 0.1, ROOM TEMPERATURE DRY CONDITIONS.

TABLE XII

PHOTOMICROGRAPH SCHEDULE OF MODMOR II/NARMCO 5206 16 PLY (0°/ ± 45°/90°) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS NUMBER OF FATIGUE (R = 0.1) LOAD CYCLES OF ROOM TEMPERATURE

Specimen No.	No. of Cycles *	Figure No.
8A-4	10,000	A-1
8A-5	10,000	A-1
8A-6	10,000	A-1
8A-7	50,000	A-2
8A-9	50,000	A-2
8A-13	50,000	A-2
8A-1	100,000	A-3
8A-14	100,000	A-3

* The load level was 185 lbs. (74.5% static ultimate load)

TABLE XIII

PHOTOMICROGRAPH SCHEDULE OF MODMOR II/NARMCO 5206 16 PLY (0°/ ± 45°/90°) COMPOSITE (WITH SCRIM CLOTH) CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS NUMBER OF FATIGUE (R = 0.1) LOAD CYCLES AT ROOM TEMPERATURE

Specimen No.	No. of Cycles*	Figure No.
7C-2	10,000	A-4
7C-10	10,000	A-4
7C-14	10,000	A-4
7C-4	50,000	A-5
7C-5	50,000	A-5
7C-6	50,000	A-5
7C-9	100,000	A-6
7C-11	100,000	A-6
7C-12	100,000	A-6

* The load level was 210 lbs (60.4% static ultimate load)

TABLE XIV

PHOTOMICROGRAPH SCHEDULE OF MODMOR II/NARMCO 5206
16 PLY (45°/135°) COMPOSITE CANTILEVER BEAM SPECIMENS
SUBJECTED TO VARIOUS NUMBER OF FATIGUE (R = 0.1) LOAD
CYCLES AT ROOM TEMPERATURE

Specimen No.	No. of Cycles *	Figure No.
3-8	10,000	A-7
3-12	10,000	A-7
3-18	10,000	A-7
3-19	50,000	A-8
3-24	50,000	A-8
3-37	50,000	A-8
3-11	100,000	A-9
3-30	100,000	A-9
3-50	100,000	A-9

* The load level was 168 lbs. (65.1% static ultimate load)

TABLE XV

PHOTOMICROGRAPH SCHEDULE OF MODMOR II/NARMCO 5206
16 PLY (45°/135°) COMPOSITE (WITH SCRIM CLOTH) CANTILEVER
BEAM SPECIMENS SUBJECTED TO VARIOUS NUMBER OF FATIGUE
(R = 0.1) LOAD CYCLES AT ROOM TEMPERATURE

Specimen No.	No. of Cycles *	Figure No.
4D-1	10,000	A-10
4D-5	10,000	A-10
4D-6	10,000	A-10
4D-24	50,000	A-11
4D-33	50,000	A-11
4D-65	50,000	A-11
4D-8	100,000	A-12
4D-34	100,000	A-12
4D-38	100,000	A-12
4D-13	500,000	A-13
4D-55	500,000	A-13
4D-60	500,000	A-13

* The load level was 174 lbs. (59.6% static ultimate load)

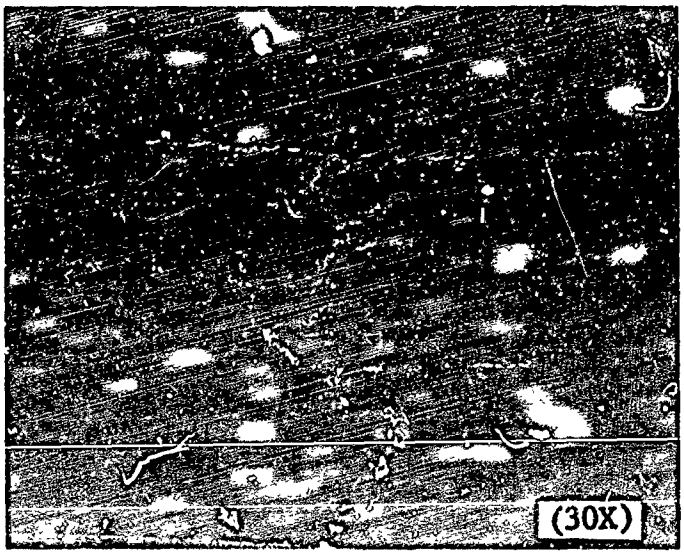


FIG. 5 CRACK DEVELOPMENT IN MODMOR II/ NARMCO 5206 16 PLY -(45° / 135°) COMPOSITE CANTILEVER BEAM SPECIMEN FAILED UNDER STATIC LOADING

of support on the tension side of the beam and progressed through the laminae; cracking spread out, from there, resulting in laminar separation and ultimate failure. It was not possible to obtain a comparable photomicrograph of the final crack pattern for fatigue loading because of difficulties in stopping the fatigue machine at the particular cycle when the failure occurs. Continued post-failure machine motion damaged the specimen. Some typical cracking patterns are shown in the following photomicrographs taken at a higher magnification (100X).

Fiber Orientation	Max. Cyclic Load (lbs)	No. of Cycles	Figure No.
(0°/± 45°/90°)	185	100,000	6
(0°/± 45°/90°) (w/scrim cloth)	210	100,000	7
(45°/135°)	168	100,000	8
(45°/135°) (w/scrim cloth)	174	500,000	9

Most of these specimens were subsectioned after they had reached an advanced stage of cracking. They all show high crack density and laminar separation.

A series of photomicrographs was obtained (Fig. A-1 through A-13 presented in Appendix "A") at various percentages of the average life at a given stress level. The crack patterns were analyzed and a plot of the percent damage, fraction of crack depth (defined or as the number of plies through which the cracks have penetrated) versus the number of stress cycles applied before sectioning of the specimen for both laminate constructions. These damage plots were made for the two fiber orientations are shown in the Figures 10 and 11. The results are not particularly informative regarding the relative performance of composites with scrim cloth interlayers.

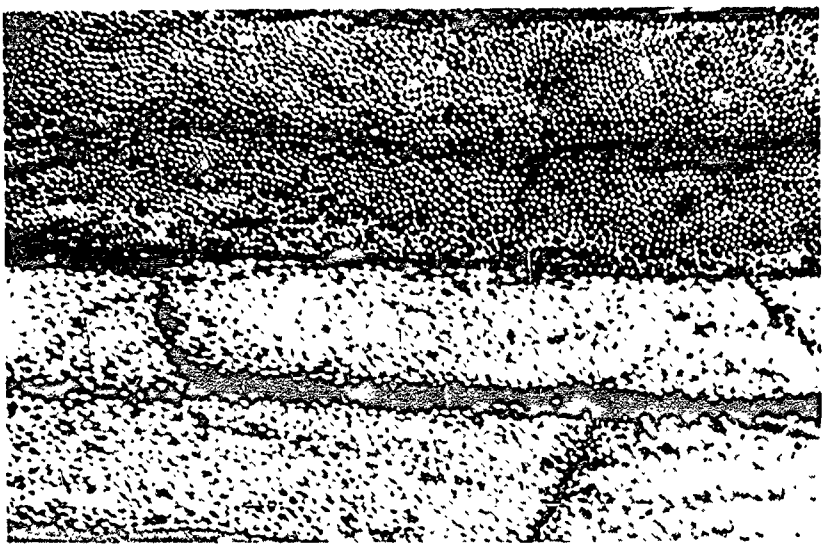


FIG. 6 CROSS SECTIONAL PHOTOMICROGRAPH OF MODMOR II/ NARMCO 5206 16 PLY COMPOSITE CANTILEVER BEAM SPECIMEN SUBJECTED TO FATIGUE (R = 0.1) STRESS CYCLES AT ROOM TEMPERATURE.

SPECIMEN NO. 8A-3, MAGNIFICATION 100X, FIBER ORIENTATION (0°/ ± 45°/90°) MAXIMUM LOAD = 185 lbs. (74.5% OF ULTIMATE) NO. OF STRESS CYCLES 100,000.

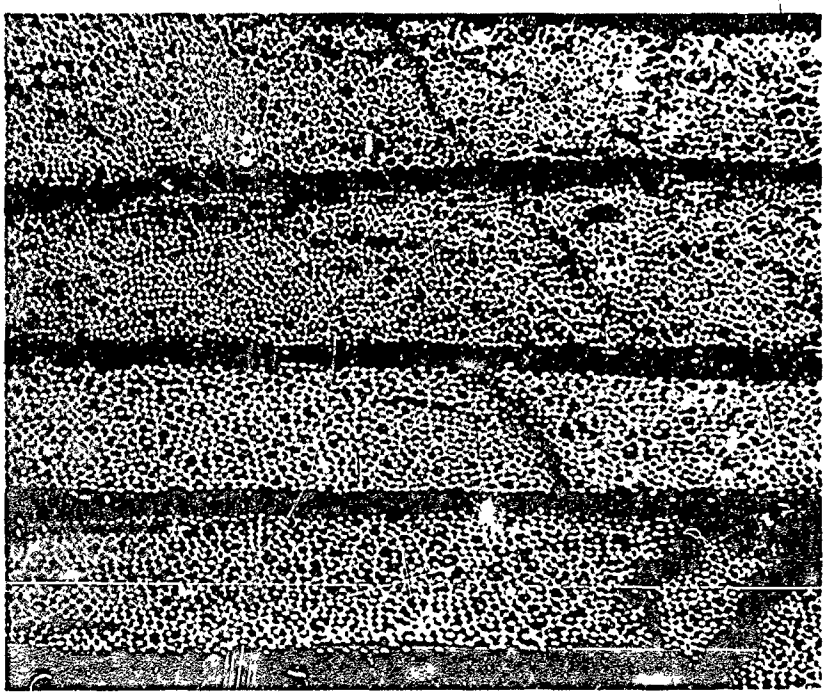


FIG. 7 CROSS SECTIONAL PHOTOMICROGRAPH OF MODMOR II/ NARMCO 5206 16 PLY COMPOSITE CANTILEVER BEAM SPECIMEN SUBJECTED TO FATIGUE (R = 0.1) STRESS CYCLES AT ROOM TEMPERATURE.

SPECIMEN NO. 7C-12 MAGNIFICATION 100X FIBER ORIENTATION 0°/ ± 45°/ 90° (WITH SCRIM CLOTH) MAXIMUM LOAD 210 LBS. (60.4% OF ULTIMATE) NO. OF STRESS CYCLES 100,000

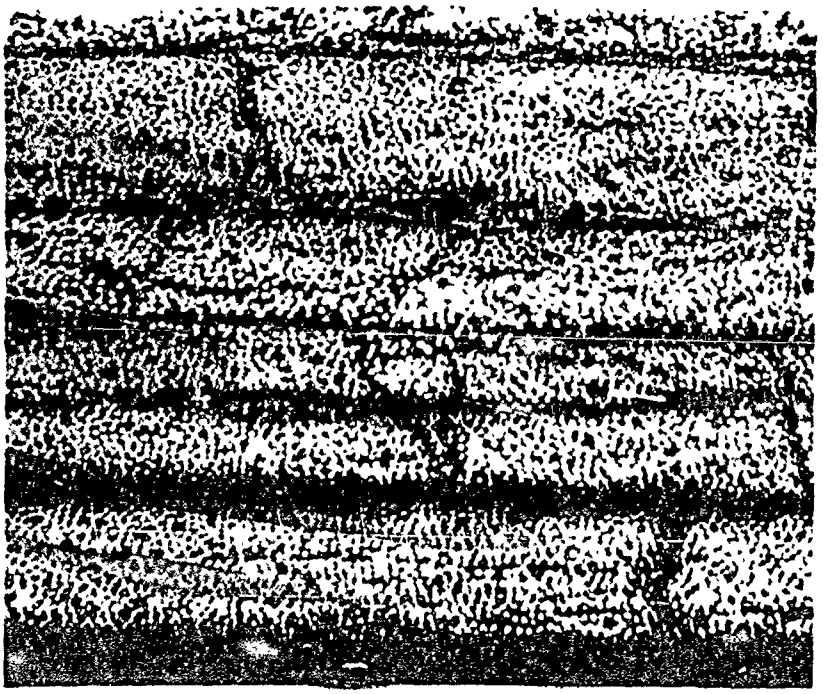


FIG. 8 CROSS SECTIONAL PHOTOMICROGRAPH OF MODMOR II/ NARMCO 5206 16 PLY COMPOSITE CANTILEVER BEAM SPECIMEN SUBJECTED TO FATIGUE (R = 0.1) STRESS CYCLES AT ROOM TEMPERATURE.

SPECIMEN NO. 3-11, MAGNIFICATION 100X, FIBER ORIENTATION 45°/ 135° MAXIMUM LOAD 168 LBS (65.1% OF ULTIMATE) NO. OF STRESS CYCLES 100,000

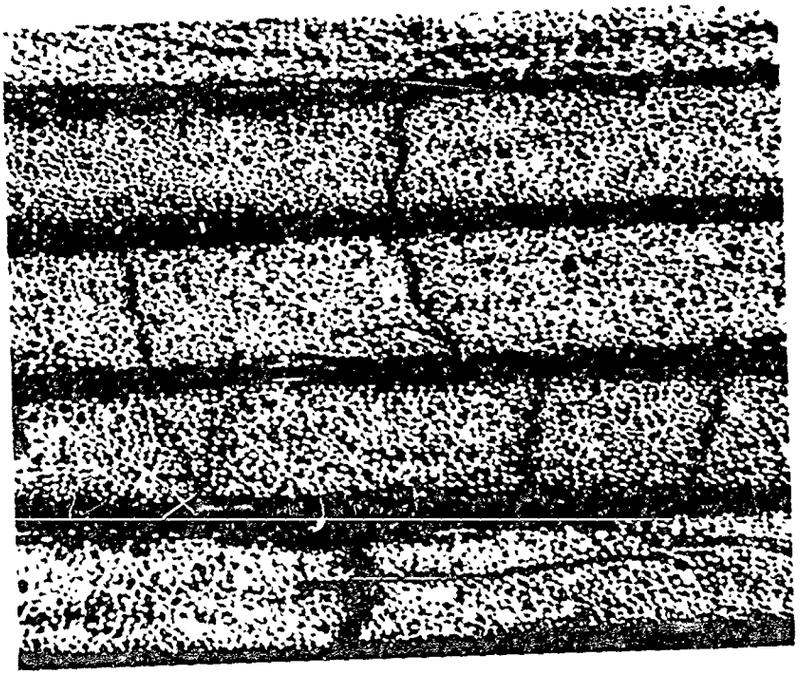


FIG. 9 CROSS SECTIONAL PHOTOMICROGRAPH OF MODMOR II/ NARMCO 5206 16 PLY COMPOSITE CANTILEVER BEAM SPECIMEN SUBJECTED TO FATIGUE (R = 0.1) STRESS CYCLES AT ROOM TEMPERATURE.

SPECIMEN NO. 4D-13, MAGNIFICATION 100X, FIBER ORIENTATION 45°/ 135° (WITH SCRIM CLOTH)
MAXIMUM LOAD 174 LBS. (59.6% OF ULTIMATE)
NO. OF STRESS CYCLES 500,000

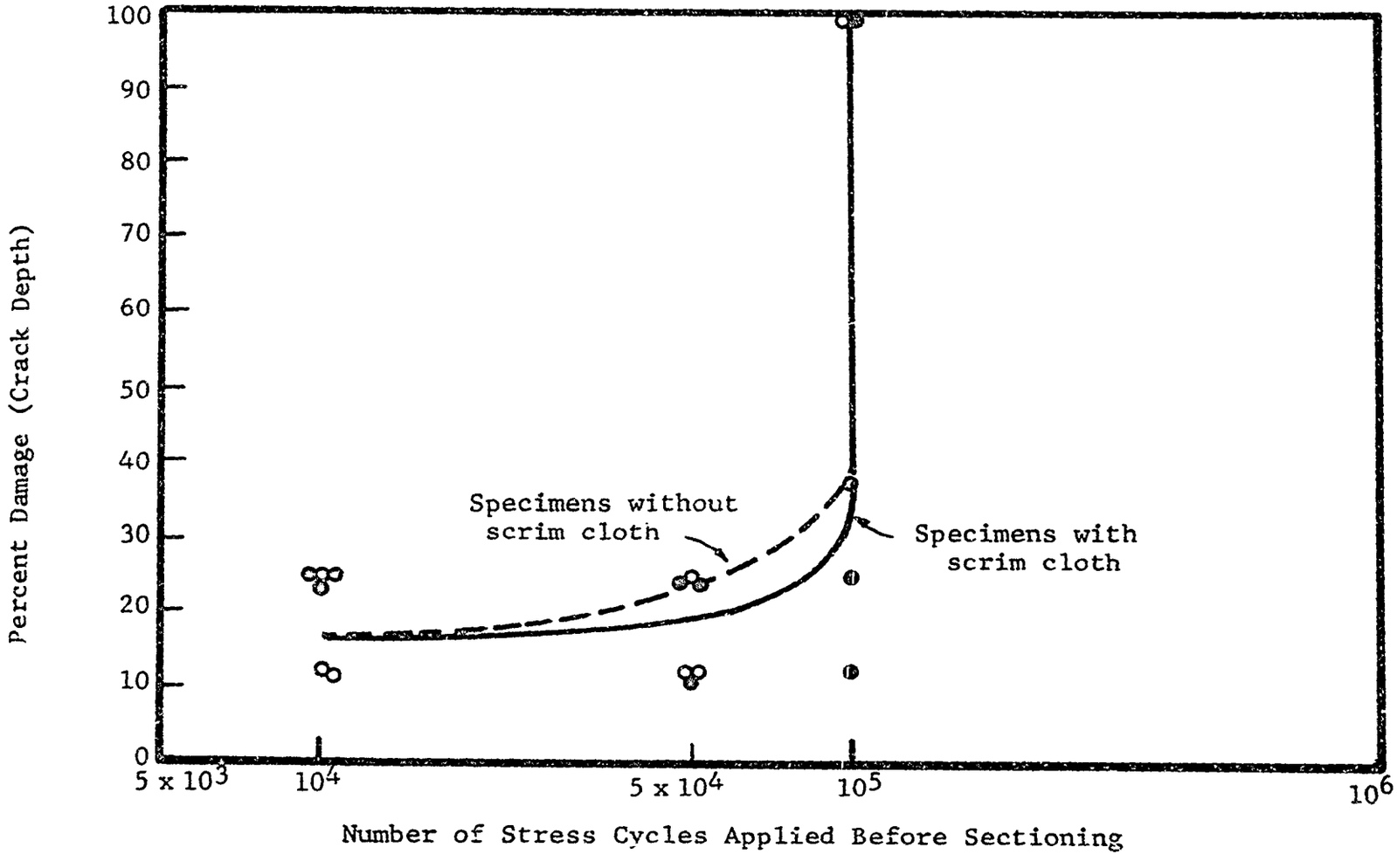


FIG. 10 PERCENT DAMAGE (CRACK DEPTH) TO MODMOR II/NARMCO 5206 16 PLY - 0°, ± 45°, 90° COMPOSITE CANTILEVER BEAM SPECIMENS INSPECTED MICROSCOPICALLY AFTER STRESS CYCLING (ROOM TEMPERATURE, DRY)

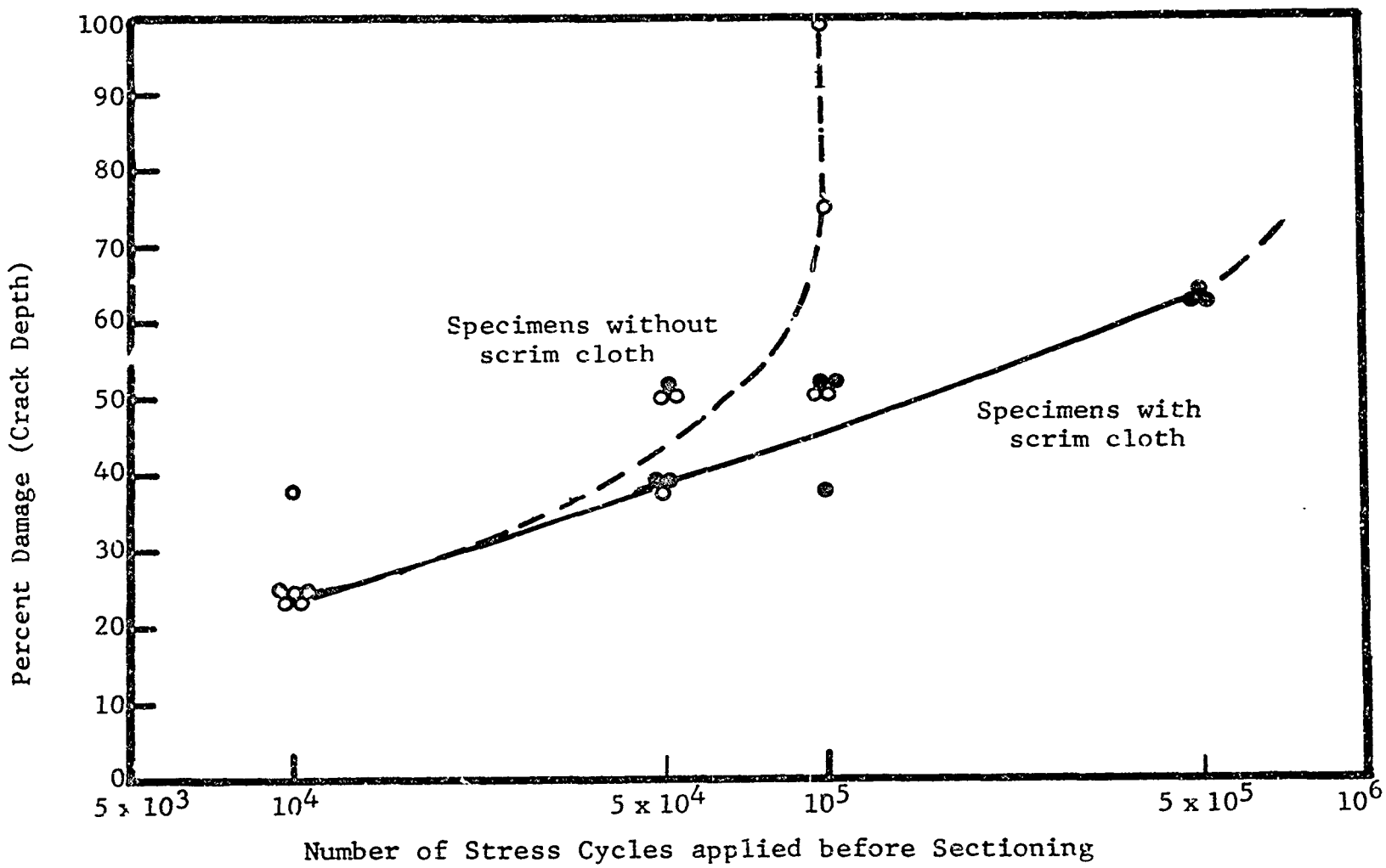


FIG. 11 PERCENT DAMAGE (CRACK DEPTH) TO MODMOR II/NARMCO 5206 16 PLY - 45°, 135° COMPOSITE CANTILEVER BEAM SPECIMENS INSPECTED MICROSCOPICALLY AFTER STRESS CYCLING (ROOM TEMPERATURE, DRY)

There is scatter apparent in the data because of discontinuous way in which the cracks penetrate plies. Laminate cracking occurs in stages, from ply to ply, following borders of tows and lamina interfaces rather than continuously as in the case of homogeneous material and thus intermediate stages of damage are not apparent.

It should be noted also that the crack depth in the cross section of the beam at the support does not give an indication of the total area in which cracking has taken place. Thus the total energy required to produce all the crack surfaces has not been accounted for in simple crack depth measurements.

The following conclusions can be drawn from this series of tests:

1. The crack development in the (45°/135°) laminate differs from the (0°/± 45°/90°) pseudoisotropic laminate in the following ways:

   (a) There is greater damage and thus earlier life termination in the (45°/135°) specimen as compared to the (0°/± 45°/90°) specimen for the same number of cycles and similar stress levels.

   (b) The pattern of cracking in (45°/135°) laminate appears (both in cross section and longitudinal section) in consecutive laminae with the progress of cycling where as in the pseudoisotropic specimens, cracking is not evident in the plies along the plane of the section.

3.4 Crack Development in Modmor II/Narmco 5206 composites Due to Variable Amplitude Stress Cycling

Use of programmed sequential block fatigue loading technique for cumulative fatigue damage assessment in composites has not yet proved to be reliable. Various theories and formulae originally applied to metals are still being tried in the case of composites. In this segment of investigation, an attempt was made to study the nature of microscopic damage, if any, occuring in sequential block loading as compared to constant amplitude fatigue loading.

The sequence of block loading selected for the present studies is shown in Table XVI. The specimens were Modmor II/5206 prepreg (45°/135°) composite cantilever beams with and without scrim cloth. The stress levels range between 65 to 79 percent of ultimate static strength for specimens without scrim cloth and 60 to 72 percent for those with scrim cloth. The high load levels were utilized to induce cracking in the specimens within a reasonable number of cycles. Other investigations[3/] have reported that cracks develop early in composite life provided the maximum cyclic stress is greater than the yield stress of the material.

Tables XVII and XVIII present a schedule of photomicrographs showing specimen number, number of spectrums and equivalent number of cycles applied and figure numbers. The figure numbers represent the photomicrographs of each of the specimen cross sections (Appendix B, Figures B-1 through B-6 at the end of this report). As for constant amplitude fatigue cycled specimens, a plot of percent damage versus number of fatigue load Sequences (instead of number of cycles) applied before sectioning of the specimens is presented in Fig. 12. Fig. 13 shows a 100X photomicrograph of a part of a

TABLE XVI

FATIGUE LOAD BLOCKS (R = 0.1) FOR MODMOR II/NARMCO 5206
16 PLY - 45° / 135° COMPOSITE CANTILEVER BEAM SPECIMENS
TESTED AT ROOM TEMPERATURE

Block No.	Shear Stress (PSI)	No. of Cycles per Spectrum	Percent of Ultimate Static Shear Strength (%)	
			No Scrim Cloth	With Scrim Cloth
1	2,800	1,000	65.1	59.6
2	3,200	20	74.4	68.1
3	3,000	100	69.8	63.8
4	3,400	10	79.1	72.4

TABLE XVII

PHOTOMICROGRAPH SCHEDULE OF MODMOR II/NARMCO 5206
16 PLY - 45° / 135° COMPOSITE CANTILEVER BEAM SPECIMENS
SUBJECTED TO VARIOUS NUMBER OF FATIGUE (R = 0.1) LOAD
BLOCKS AT ROOM TEMPERATURE

Specimen No.	No. of Spectrums	No. of Cycles	Figure No.
3-3	22	25,000	B-1
3-26	22	25,000	B-1
3-20	45	50,000	B-2
3-25	45	50,000	B-2
3-29	67	75,000	B-3
3-33	67	75,000	B-3
3-43	67	75,000	B-3

TABLE XVIII

PHOTOMICROGRAPH SCHEDULE OF MODMOR II/NARMCO 5206 (WITH SCRIM CLOTH) 16 PLY - 45° / 135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS NUMBERS OF FATIGUE (R = 0.1) LOAD BLOCKS AT ROOM TEMPERATURE

Specimen No.	No. of Spectrums	No. of Cycles	Figure No.
4D-2	45	50,000	B-4
4D-11	45	50,000	B-4
4D-22	90	100,000	B-5
4D-27	90	100,000	B-5
4D-28	90	100,000	B-5
4D-35	135	150,000	B-6
4D-41	135	150,000	B-6
4D-57	135	150,000	B-6

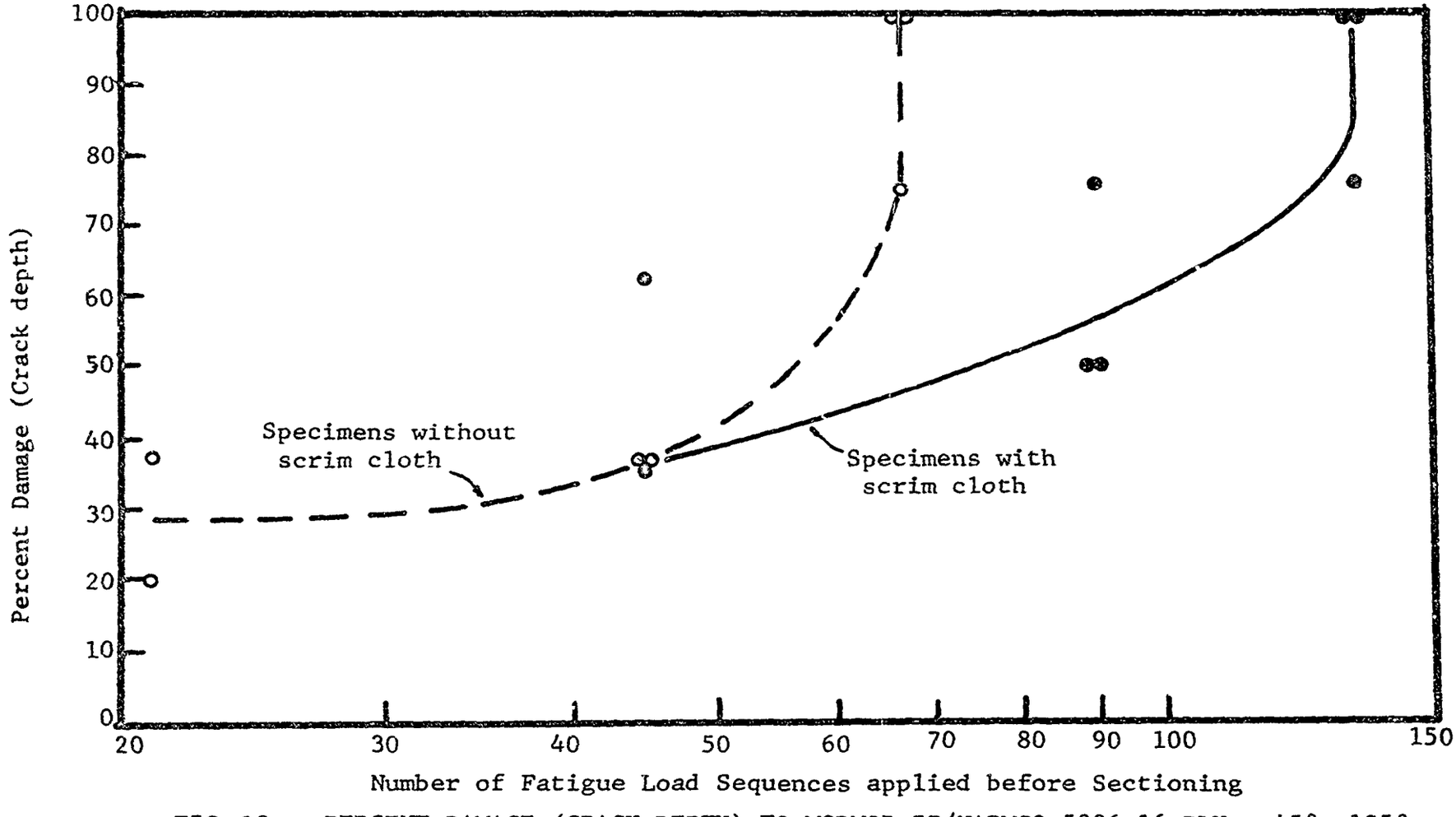


FIG. 12 PERCENT DAMAGE (CRACK DEPTH) TO MODMOR II/NARMCO 5206 16 PLY - 45°, 135° COMPOSITE CANTILEVER BEAM SPECIMENS INSPECTED MICROSCOPICALLY AFTER SEQUENTIAL LOAD FATIGUE (R = 0.1) STRESS CYCLING (ROOM TEMPERATURE, DRY.)

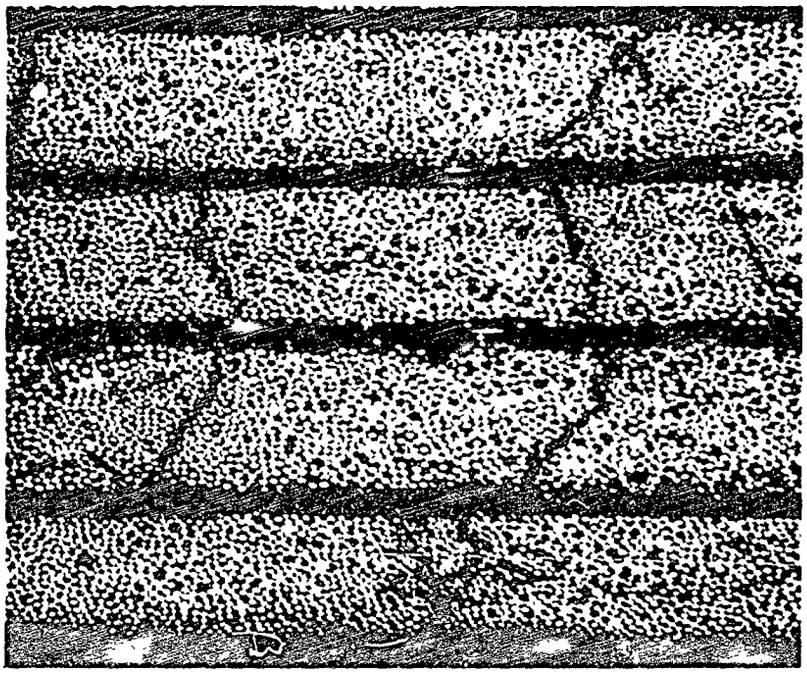


FIG. 13 CROSS SECTIONAL PHOTOMICROGRAPH OF MODMOR II/ NARMCO 5206 16 PLY COMPOSITE CANTILEVER BEAM SPECIMEN SUBJECTED TO FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE.

SPECIMEN NO. 4D-41, MAGNIFICATION 100X, FIBER ORIENTATION 45°, 135° (WITH SCRIM CLOTH) NO. OF BLOCKS 135.

damaged specimen sectioned after applying 135 Blocks.

From this series of tests the following conclusions can be drawn.

1. Here there is a definite improvement in the composites resistance to fatigue damage when scrim cloth is added to the composite.

2. The crack growth appears to follow along the same lines as with constant amplitude stress cycling except for the single feature that interlaminar crackings appears to be more prevalent in the Sequential Fatigue loading than in the constant amplitude counterpart for the material with no scrim cloth interlayers. This gives added credance to the philosophy that the scrim cloth interlayers will play an important role in alleviating interlaminar cracking for laminates subjected to repeated stress cycling.

4.0 AGING PROBLEMS OF MODMOR II/NARMCO 5206 COMPOSITES

The performance of graphite/epoxy composite material at elevated temperature is of concern to composites designers. Recently, degradation of composite elevated temperature flexure strength with ambient aging has been detected. Initially the problem was thought to be a result of poor thermal stability of resin[4/], as longitudinal flexural strengths of HT-S/X-904 composites dropped rapidly with increase of temperatures particularly above 200°F. Further investigation showed that some of the early panels that had previously provided acceptable strength values when tested now showed great strength reduction. Further data from Convair Aerospace, Fiberite, Hercules, and Whittaker Corporations on longitudinal flexural strengths of unidirectional laminates led to the recognition of the problem of flexural strength reduction at elevated temperatures due to ambient aging. Similar reductions were also noticed in horizontal shear strengths at 350°F. Later studies at Convair[5/] showed severe reduction in compression strength of FMS-2021A Class I graphite composite at 300°F due to ambient aging. This work attributed the phenomenon to moisture absorption by the composite. A weight gain of between 1 to 3-1/2 percent by weight when exposed to a relative humidity of 98% for 150 days was measured. In spite of this, the graphite composites, (in a recent investigation by Grumman Aerospace Corporation)[4/] showed no tensile strength deterioration at 375°F when aged at room temperature.

The phenomenon of ambient aging effect is not unique to graphite/epoxy composites only. In another study[6/], Grumman Aerospace Corporation reported similar results for Boron/5505 composite. In the case of fiberglass composites, most of the available data is on the evaluation of room temperature properties after various exposures and the development of silicone finishes

seems to have limited the R.T. strength degradation.

4.1 Possible causes of thermal instability in graphite/epoxy composites due to ambient aging

There are several possible reasons for elevated temperature strength reduction due to ambient aging. Mechanisms in bringing about this phenomenon are suggested by various investigators. Most of these are related to resin material problems such as oxidation and hydrolysis or resins. But the fiber material could contribute to this problem because of its surface effects and its thermal property differences between fiber and matrix materials.

Many investigators attribute the aging problem to water absorption by the matrix. Plasticization, molecular scission or other chemical reactions are said to occur triggering the strength deterioration problem. Another suggested theory is the detrimental effect of absorbed moisture expelled from the matrix in the form of steam at elevated temperatures that causes the strength reduction.

4.2 Aging Effects on Modmor II/5206 Composite Flexural Strength

The reasons for undertaking the aging effects studies are two-fold:

1. To assess the extent of the ambient aging effect on elevated temperature flexural strengths of Modmor II/5206 composite on two ply orientations namely (0°/90°) orthogonal layup and (0°/± 45°/90°) pseudoisotropic configuration. For this purpose the test program consisting of three series of flexural strength tests were conducted as follows:

   (a) 'No aging' specimens which were tested within 48 hours of fabrication, at room temperatures and

other elevated temperatures up to 300°F.

(b) 'Laboratory Exposed' specimens were those that were stored for 5 weeks in the laboratory (72 ± 3°F and 50% R.H.) and tested at the end of the period.

(c) 'Accelerated aging' specimens were those that were placed in a steady state environmental chamber for 5 weeks at a temperature of 120° ± 5°F and 95 ± 2% R.H. and tested at the end of the exposure period.

The accelerated aging test program would provide information on the ambient aging effects that might be encountered in high humidity field conditions.

2. In view of earlier experience at IITRI of obtaining improved performance of various composites (including Modmor II/5206 system) by addition of glass 104 - 20 x 20 scrim cloth as interlayers between plies, it was decided to investigate whether any improvement in elevated temperature flexural strength degradation can be effected in laboratory aged specimens as well as in specimens subjected to accelerated aging both compared to specimens that were tested immediately after fabricating.

4.3 Flexural strength tests of Modmor II/5206 Composite Specimens

The flexural specimens were 1/2 in. wide and 5 in. long and provided an effective test span of 4 in. which satisfied the minimum span to depth ratio of 30. However, in the case of (0°/± 45°/90°) composite specimens with scrim cloth, an effective span of 3 in. was employed (except for "no aging" specimens) due to limited composite plate size available for specimen fabrication after

discarding part of the plate that appeared to be of doubtful quality.

All specimens were soaked for a period of 30 minutes at the test temperature prior to testing. The accelerated aging specimens were weighed before and after exposure. The percent increase in weight due to absorption of water was found to be less than one percent. (Tables IX through XXI)

The flexure tests were conducted on an Instron Universal testing machine, single point loading and flexural strength was obtained from the formula:

$$\sigma = \frac{3PL}{2wt^2}$$

where σ = Flexural Stress, psi

P = Peak load, lbs.

L = Effective Span, in.

w = Specimen width, in.

t = Specimen thickness, in.

The results of these tests are presented in the following Tables and Figures:

(0°/90°)	Table XXII	Fig. 14
(0°/90°) (w/scrim cloth)	Table XXIII	Fig. 15
(0°/± 45°/90°)	Table XXIV	Fig. 16
(0°/± 45°/90°) (w/scrim cloth	Table XXV	

Fig. 17 shows the comparative flexural strength performance of (0°/90°) systems with and without scrim cloth.

The results of the aging studies can be summarized as follows:

1. At room temperature, within the limits of experimental error there is no effect of ambient aging (laboratory

TABLE XIX

MOISTURE ABSORPTION OF MODMOR II/NARMCO 5206
16 PLY PREPREG (0°/90°) COMPOSITE SPECIMENS
EXPOSED FOR 5 WEEKS TO 95 ± 2% RH AT 120°F

Specimen Number	Initial wt. of Specimens (gms)	Wt. of Specimen After Exposure (gms)	Increase in Wt. of Specimens (percent)
F-1	7.6669	7.7248	0.76
F-3	8.2275	8.2905	0.76
F-8	8.1331	8.1995	0.72
F-14	8.0025	8.0654	0.79
F-19	7.8008	7.8662	0.83
F-20	7.9567	8.0187	0.78
F-23	8.1384	8.2041	0.81
F-26	7.5928	7.6554	0.82
F-27	7.9255	7.9966	0.89
F-29	7.8525	7.9152	0.79
F-30	7.8795	7.9391	0.75
F-32	8.2264	8.3937	0.81
F-36	7.8686	7.9336	0.82
F-37	7.9424	8.0086	0.83
F-39	7.8293	7.8898	0.77

TABLE XX

MOISTURE ABSORPTION OF MODMOR II/NARMCO 5206 16 PLY PREPREG (0°/90°) COMPOSITE (WITH SCRIM CLOTH) SPECIMENS EXPOSED FOR 5 WEEKS TO 95 ± 2% RH AT 120°F

Specimen Number	Initial Wt. of Specimen (gms)	Wt. of Specimen After Exposure (gms)	Increase in Wt. of Specimen (percent)
H-1	8.5353	8.6003	0.76
H-7	8.5702	8.6353	0.75
H-12	8.5357	8.6007	0.76
H-14	8.1353	8.1964	0.75
H-16	8.6658	8.7333	0.77
H-26	8.4935	8.5584	0.76
H-27	8.4295	8.4938	0.76
H-28	8.1919	8.2523	0.73
H-32	8.3119	8.3721	0.72
H-33	8.2974	8.3567	0.71
H-35	8.4302	8.4895	0.70
H-36	8.0987	8.1583	0.73
H-39	8.4168	8.4765	0.71
H-40	8.2064	8.2638	0.69
H-41	8.3051	8.3669	0.74

TABLE XXI

MOISTURE ABSORPTION OF MODMOR II/NARMCO 5206
16 PLY PREPREG (0°/ ± 45°/90°) COMPOSITE SPECIMENS
EXPOSED FOR 5 WEEKS TO 95 ± 2% RH AT 120°F

Specimen Number	Initial Wt. of Specimens (gms)	Wt. of Specimen After Exposure (gms)	Increase in Wt. of Specimens (percent)
E-1	7.4764	7.5335	0.76
E-7	8.1418	8.1987	0.69
E-12	8.1977	8.2575	0.72
E-22	8.1063	8.1669	0.74
E-27	7.9413	7.9981	0.71
E-28	7.9455	8.0035	0.72
E-31	3223	8.3839	0.74
E-33	[illegible]	8.2344	0.72
E-34	8.1003	8.1579	0.71
E-36	8.1571	8.2167	0.73
E-41	8.1437	8.2002	0.69
E-43	7.9991	8.0546	0.69

Table XXII

FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES
16 PLY - 0°, 90°, PLY ORIENTATION SUBJECTED TO VARIOUS
AGING CONDITIONS

NO AGING			LABORATORY EXPOSURE (5 Weeks)			ACCELERATED AGING (5 Weeks)*		
SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi
F-2	RT	117.2	F-5	RT	116.0	F-1	RT	101.2
F-6	RT	103.1	F-11	RT	109.0	F-3	RT	110.0
F-10	RT	121.4				F-8	RT	109.7
F-13	RT	120.7						
F-18	RT	117.1						
AVERAGE		115.9			112.5			107.6
% Strength Retained**		100			97			93
F-7	200°	110.9	F-17	200°	99.8	F-14	200°	83.9
F-31	200°	102.3	F-21	200°	106.0	F-19	200°	94.7
F-35	200°	100.7				F-20	200°	82.6
AVERAGE		104.6			102.9			87.1
% Strength Retained**		90			89			75
F-25	250°	90.0	F-22	250°	76.0	F-29	250°	63.0
F-28	250°	88.3	F-24	250°	71.0	F-30	250°	62.3
F-33	250°	90.0				F-32	250°	57.3
AVERAGE		89.4			73.5			60.9
% Strength Retained**		77			72			59
						F-36	275°	36.0
						F-37	275°	34.8
						F-39	275°	36.0
						AVERAGE		35.6
F-4	300°	75.7	F-34	300°	46.0	F-23	300°	28.9
F-9	300°	53.0	F-38	300°	30.7	F-26	300°	26.3
F-12	300°	40.7				F-27	300°	24.0
F-15	300°	44.7						
F-16	300°	49.9						
AVERAGE		52.8			38.4			26.4
% Strength Retained**		46			33			23

* Accelerated Aging in 95 ± 2% RH at 120°F

** % of Original Flexural Strength at the Room Temperature

Table XXIII

FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES
16 PLY - 0°, 90°, PLY ORIENTATION (SCRIM CLOTH) SUBJECTED
TO VARIOUS AGING CONDITIONS

NO AGING			LABORATORY EXPOSURE (5 Weeks)			ACCELERATED AGING (5 Weeks)*		
SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi
H-3	RT	117.2	H-6	RT	124.0			
H-8	RT	118.6	H-9	RT	122.8	H-7	RT	128.9
H-11	RT	125.6	H-10	RT	128.9	H-12	RT	123.3
H-20	RT	130.2						
H-22	RT	134.8						
AVERAGE		125.3			125.2			126.1
% Strength Retained**		100			100			100
H-2	200°	124.1	H-17	200°	101.9	H-14	200°	86.8
H-4	200°	120.7	H-21	200°	98.2	H-16	200°	104.2
H-15	200°	122.0	H-24	200°	97.7	H-26	200°	87.0
AVERAGE		122.3			99.3			92.7
% Strength Retained**		98			79			74
H-23	250°	113.8	H-25	250°	78.8	H-33	250°	74.5
H-29	250°	90.3	H-31	250°	82.1	H-35	250°	66.2
H-30	250°	100.5	H-37	250°	75.3	H-36	250°	52.3
AVERAGE		101.5			78.7			64.3
% Strength Retained**		81			63			51
						H-39	275°	39.5
						H-40	275°	39.3
						H-41	275°	37.7
						AVERAGE		38.8
H-5	300°	74.8	H-38	300°	45.8	H-27	300°	31.7
H-13	300°	61.4	H-42	300°	36.6	H-28	300°	27.2
H-18	300°	57.3				H-32	300°	24.8
H-19	300°	55.8						
H-34	300°	68.4						
AVERAGE		63.5			41.2			27.9
% Strength Retained**		51			33			22

* Accelerated Aging in 95 ± 27 RH at 120°F

** % of Original Flexural Strength at the Room Temperature

Table XXIV

FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES
16 PLY - 0°, 90°, + 45° PLY ORIENTATION SUBJECTED TO
VARIOUS AGING CONDITIONS

NO AGING			LABORATORY EXPOSURE (5 Weeks)			ACCELERATED AGING (5 Weeks)*		
SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi
E-4	RT	85.2				E-1	RT	76.1
E-6	RT	91.4				E-7	RT	76.0
E-16	RT	64.9				E-12	RT	74.2
E-18	RT	82.6						
E-32	RT	70.1						
AVERAGE		78.8						75.4
% Strength Retained**		100						96
E-10	200°	72.8	E-24	200°	65.5	E-22	200°	65.6
E-20	200°	63.6				E-27	200°	55.0
E-21	200°	67.7				E-28	200°	61.4
E-35	200°	72.6						
E-37	200°	61.4						
AVERAGE		67.6						60.7
% Strength Retained**		86			81			77
E-17	250°	57.9	E-29	250°	56.0	E-36	250°	40.4
E-25	250°	56.4				E-41	250°	44.3
E-26	250°	55.9				E-43	250°	42.5
AVERAGE		56.7						42.4
% Strength Retained**		72			71			54
E-5	275°	48.8	E-38	275°	40.0			
E-11	275°	41.9						
E-14	275°	50.8						
AVERAGE		47.2						
% Strength Retained**		60			50			
E-3	300°	41.6	E-42	300°	33.1	E-31	300°	31.7
E-8	300°	36.7				E-33	300°	29.3
E-19	300°	28.3				E-34	300°	25.3
E-30	300°	36.7						
E-39	300°	30.7						
AVERAGE		34.8						28.8
% Strength Retained**		44			42			37

* Accelerated Aging in 95 ± 2% RH at 120°F

** % of Original Flexural Strength at the Room Temperature

Table XXV

FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES
16 PLY - 0°,90°, ± 45° PLY ORIENTATION (SCRIM CLOTH)
SUBJECTED TO VARIOUS AGING CONDITIONS

NO AGING			LABORATORY EXPOSURE (5 Weeks)			ACCELERATED AGING (5 Weeks)*		
SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH *** ksi	SPEC. NO.	TEST TEMP°F	FLEXURE STRENGTH *** ksi
G-2	RT	85.1	G-6	RT	77.6			
G-22	T	73.9	G-13	RT	82.9			
G-17	RT	83.7						
AVERAGE		80.9			80.3			
% Strength Retained **		100			98			
G-7	200	62.1	G-5	200	56.5			
G-8	200	62.1	G-9	200	66.4			
G-20	200	60.7						
AVERAGE		61.6			61.5			
% Strength Retained **		76			76			
G-1	300	63.5	G-4	300	61.7	G-14	300	49.8
G-18	300	51.5	G-10	300	52.3	G-16	300	49.8
G-21	300	57.8						
AVERAGE		57.6			57.0			49.8
% Strength Retained **		71			70			62

* Accelerated Aging in 95 ± 2% RH at 120°F

** % of Original Flexural Strength at the Room Temperature

*** These results are for flexural Specimens with a span of 3 inches as compared to "NO AGING" specimens which were of 4 inch span.

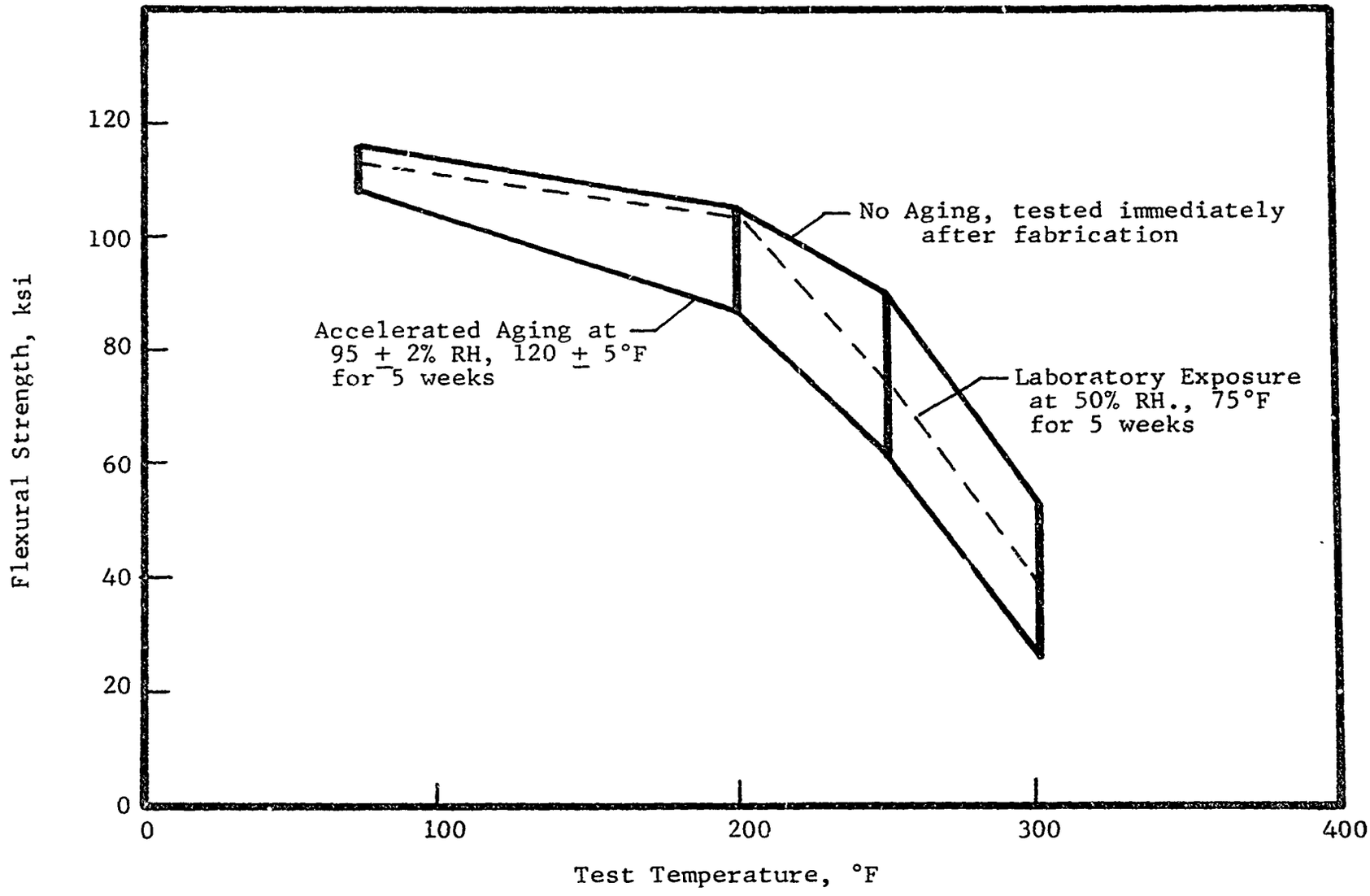


FIG. 14 FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES, 16 PLY - 0°, 90° PLY ORIENTATION

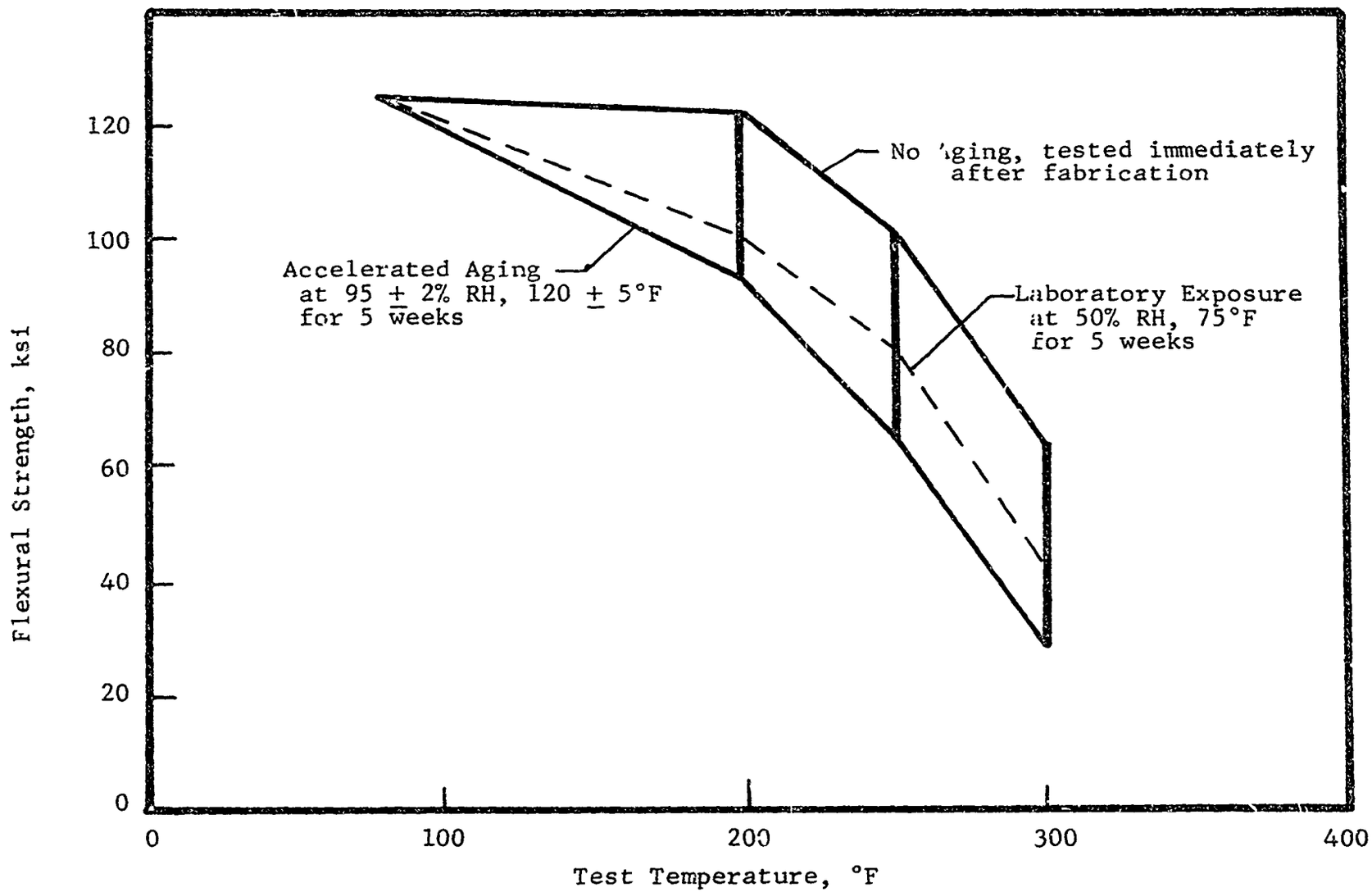


FIG. 15 FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES, 16 PLY - 0°, 90° PLY ORIENTATION (WITH SCRIM CLOTH)

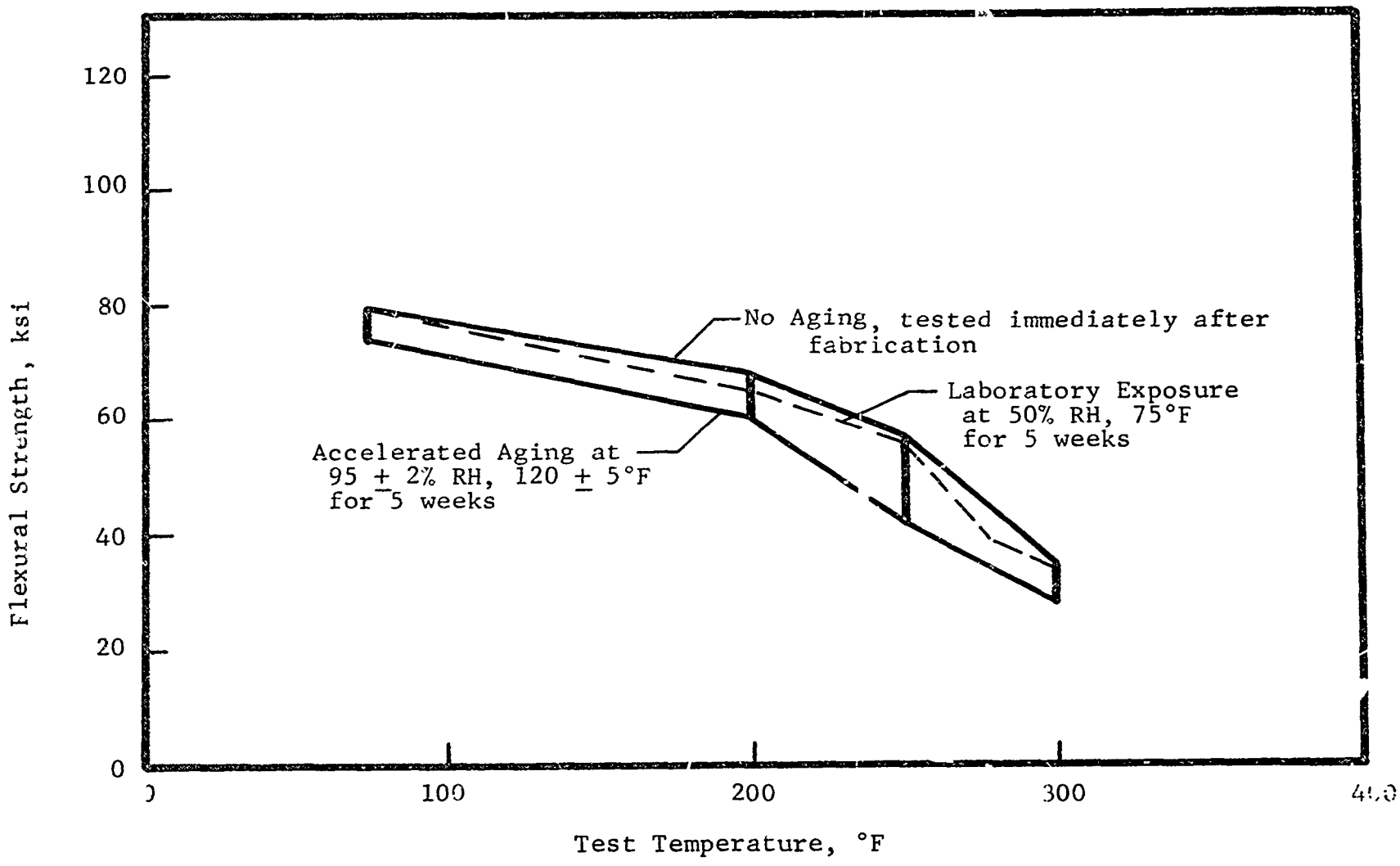


FIG. 16 FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES, 16 PLY - 0°, 90° ± 45° PLY ORIENTATION

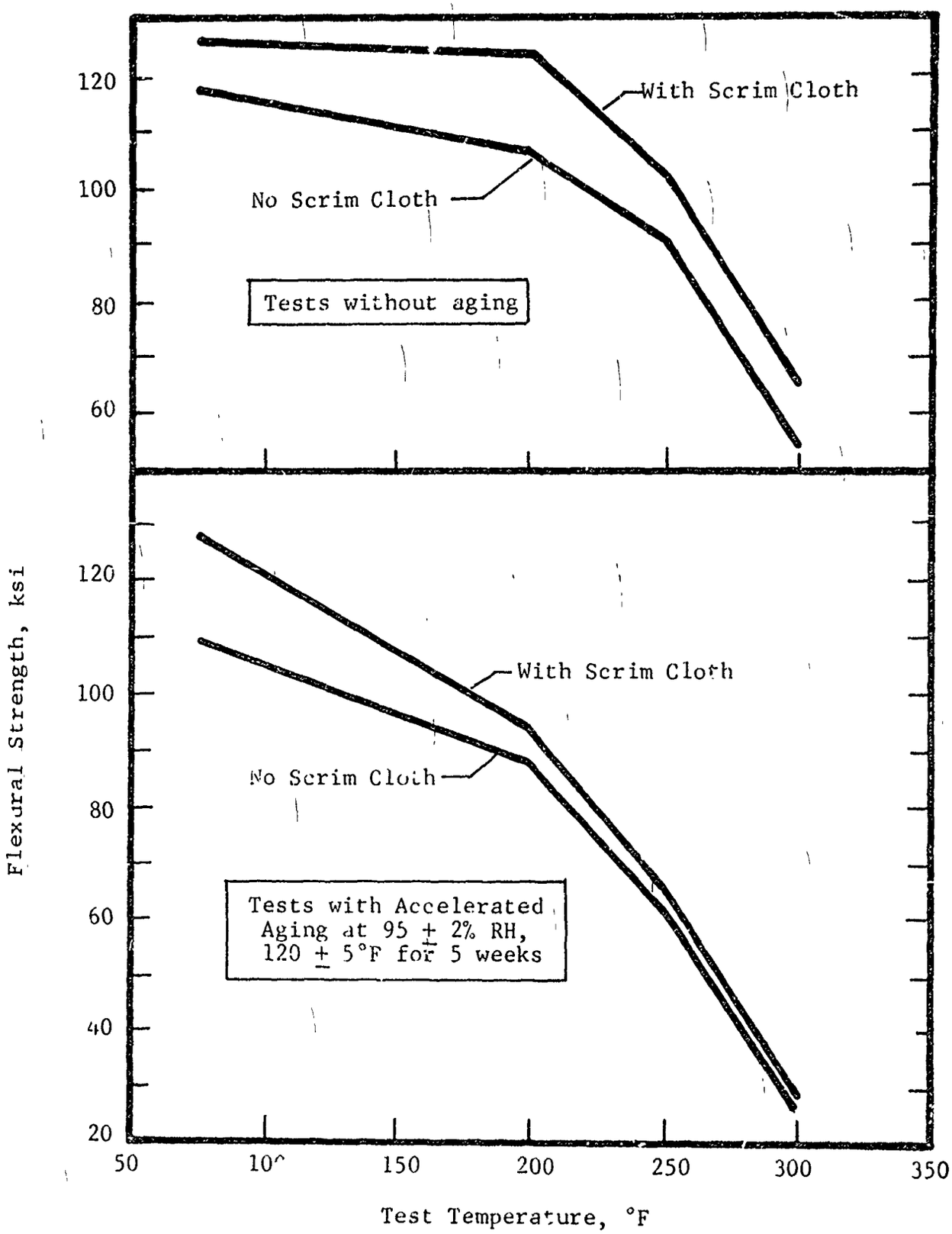


FIG. 17 FLEXURAL STRENGTHS OF MODMOR II/NARMCO 5206 COMPOSITES, 16 PLY - 0°, 90°, PLY ORIENTATION

exposure) on the flexural strengths of any of the composite systems studies.

2. Flexural strength reduction due to ambient aging in specimens tested at room temperature is minimum in all cases and doesn't occur in (0°/90°) (scrim cloth) specimens.

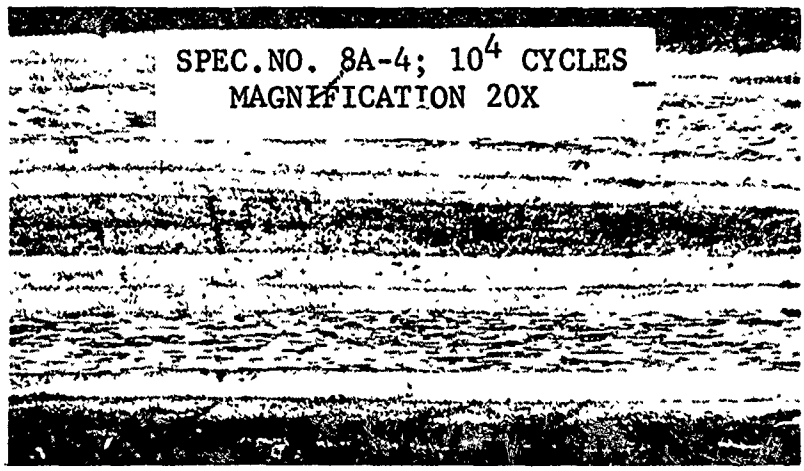
3. It appears that the flexural strength reductions due to ambient aging in specimens tested at elevated temperatures are considerable particularly in (0°/90°) (scrim cloth) specimens, although they are less severe than those for accelerated aging specimens.

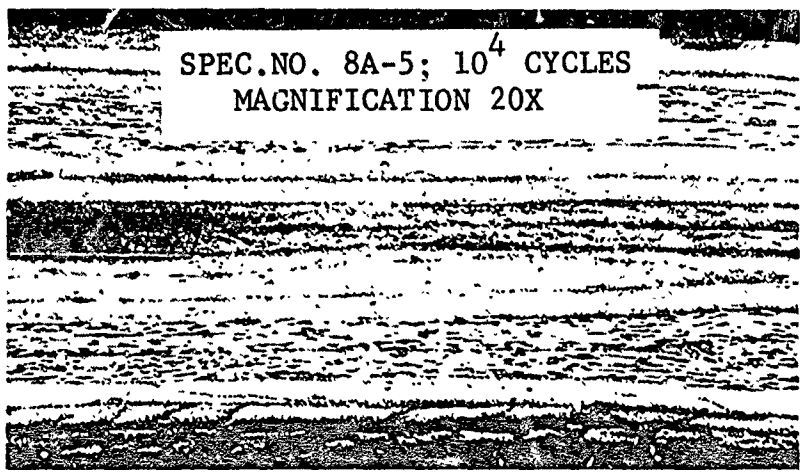
4. There is a pronounced strength degradation at elevated temperatures due to accelerated aging in all cases.

5. The flexural strength data indicate that there is a composite strength improvement due to the addition of scrim cloth interlayers both at room temperature and elevated temperatures.

APPENDIX A

PHOTOMICROGRAPHS OF GRAPHITE/EPOXY COMPOSITE SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES





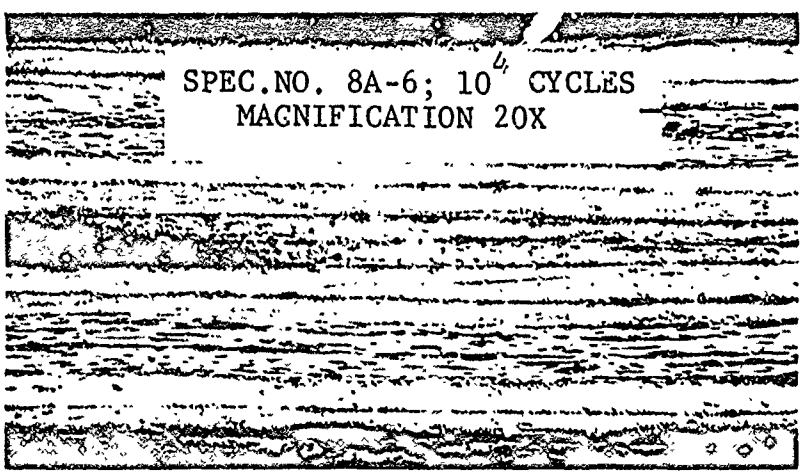


FIG. A-1 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 0°/ ± 45°/90° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 185 LBS), ROOM TEMPERATURE, DRY.

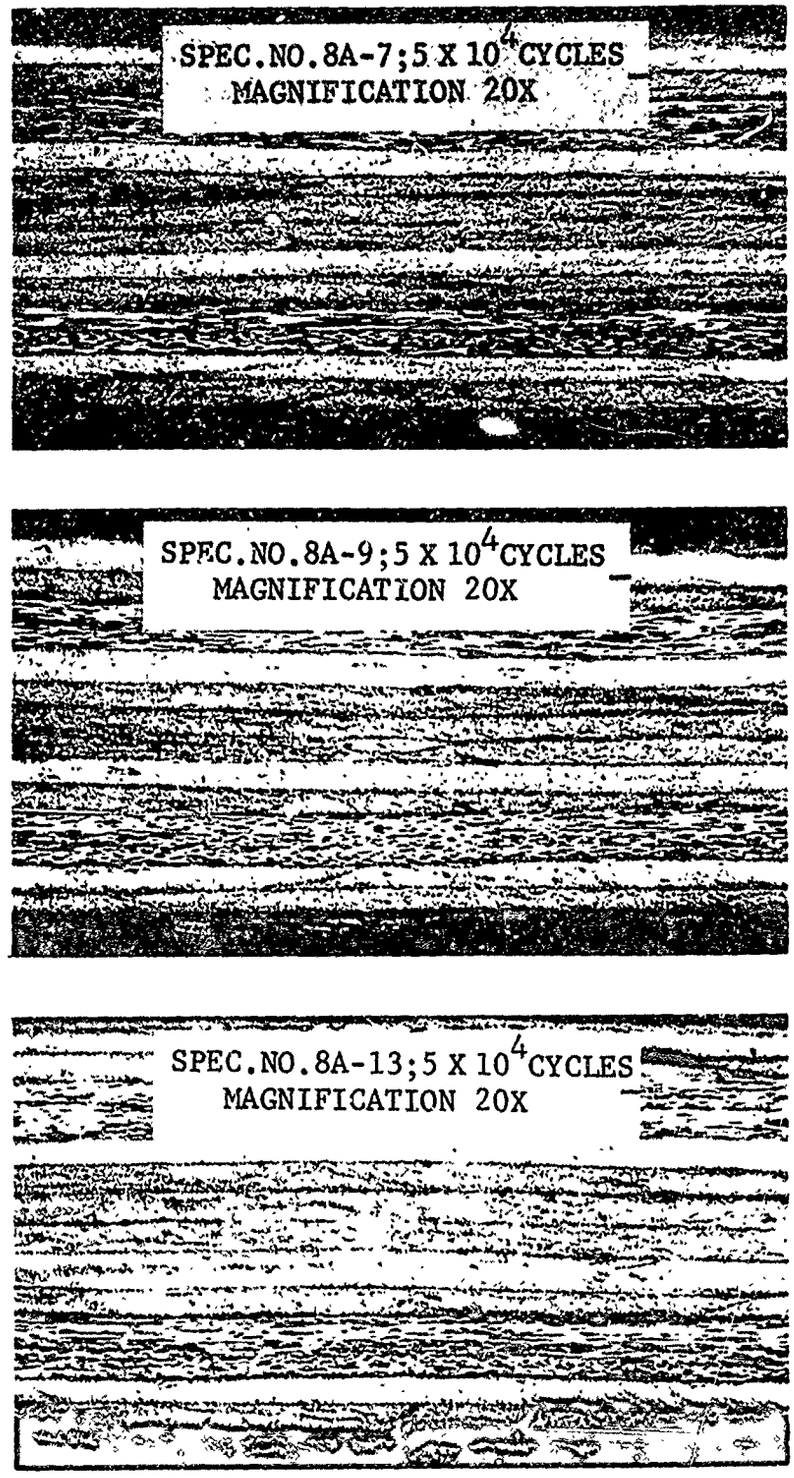
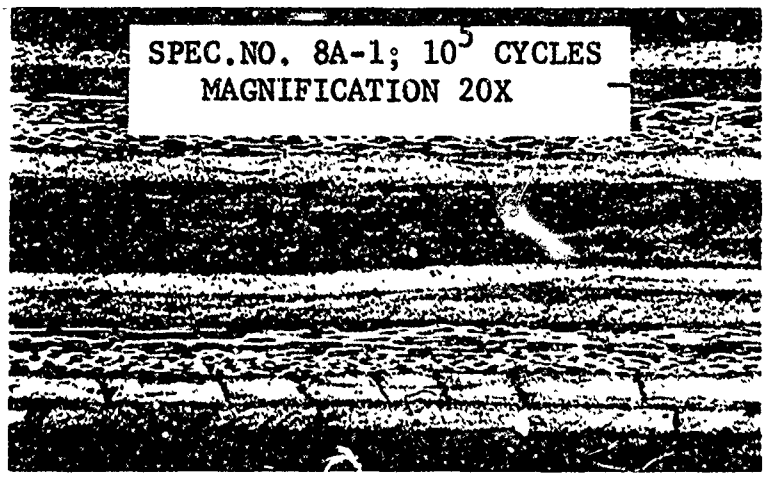


FIG. A-2 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 0°/ ± 45°/90° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 185 LBS), ROOM TEMPERATURE, DRY.



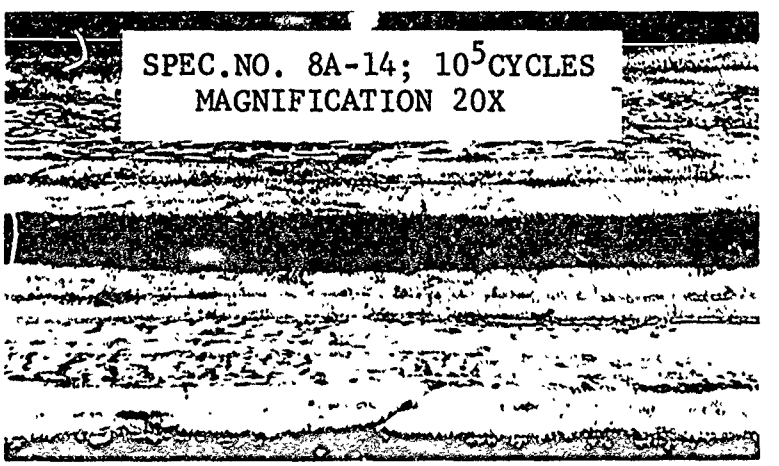
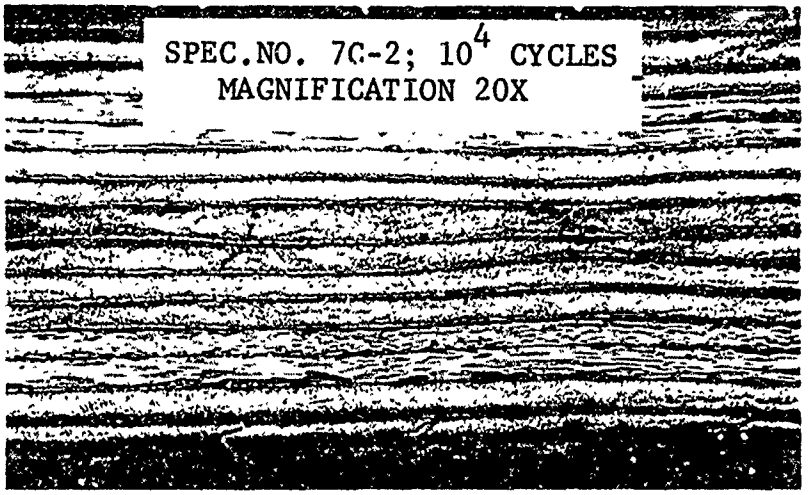
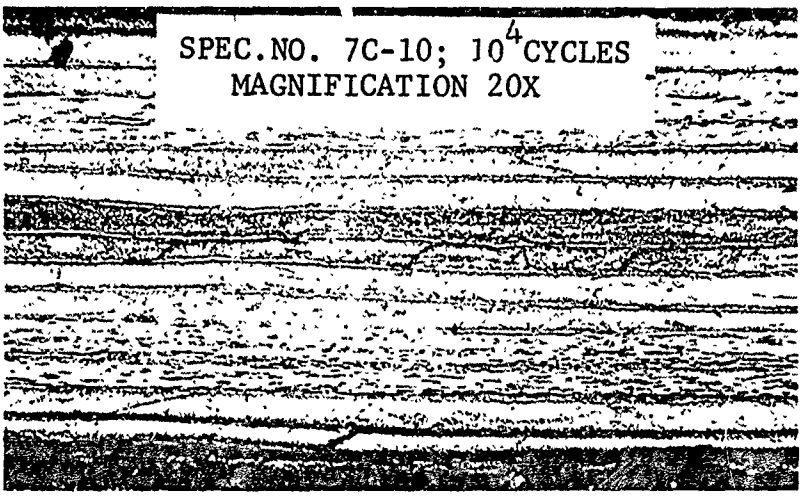


FIG. A-3 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 0°/ ± 45°/90° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 185 LBS), ROOM TEMPERATURE, DRY.





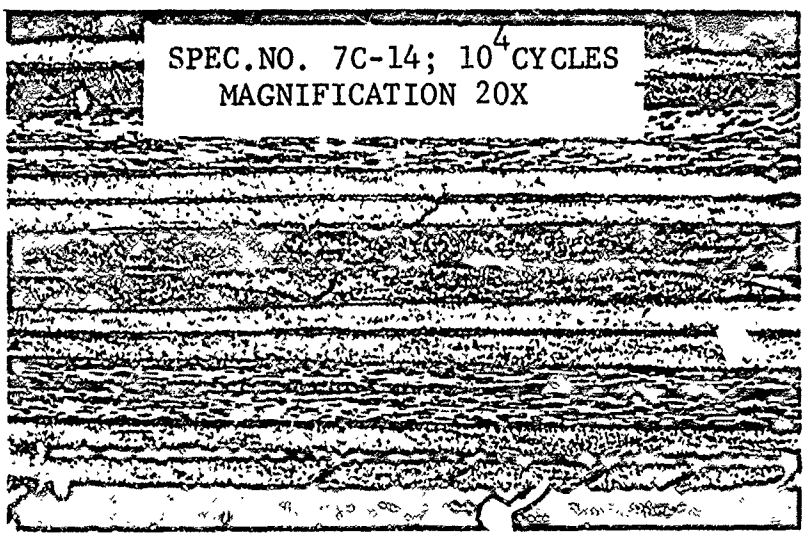
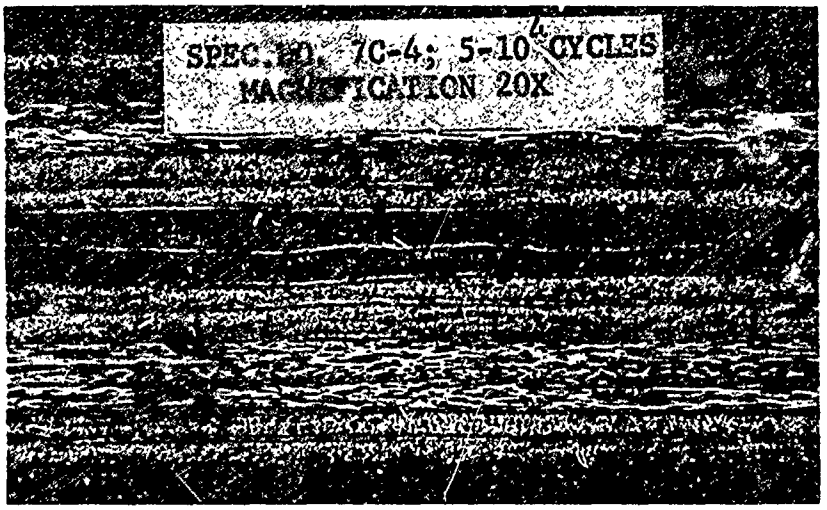
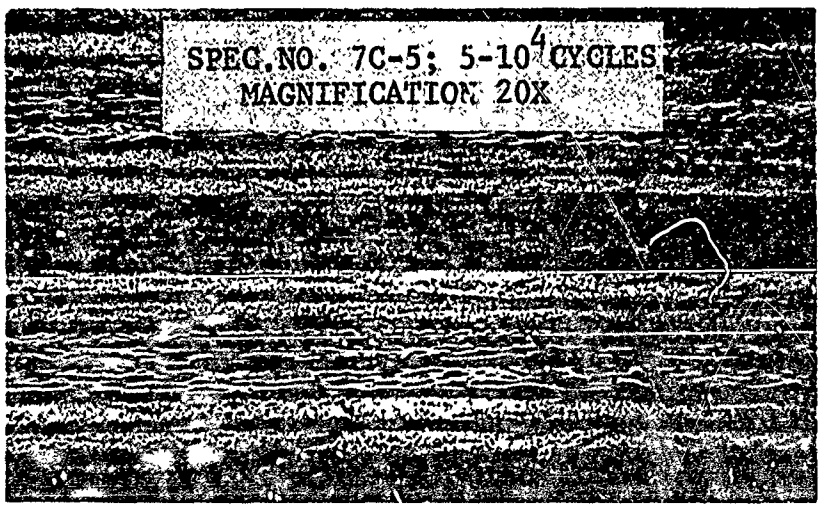


FIG. A-4 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 0°/ ± 45°/90° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 210 LBS), ROOM TEMPERATURE, DRY.





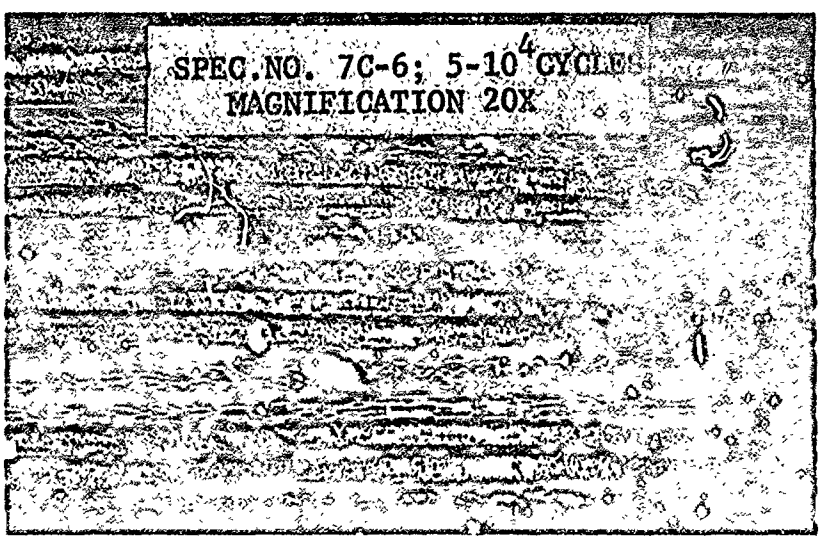
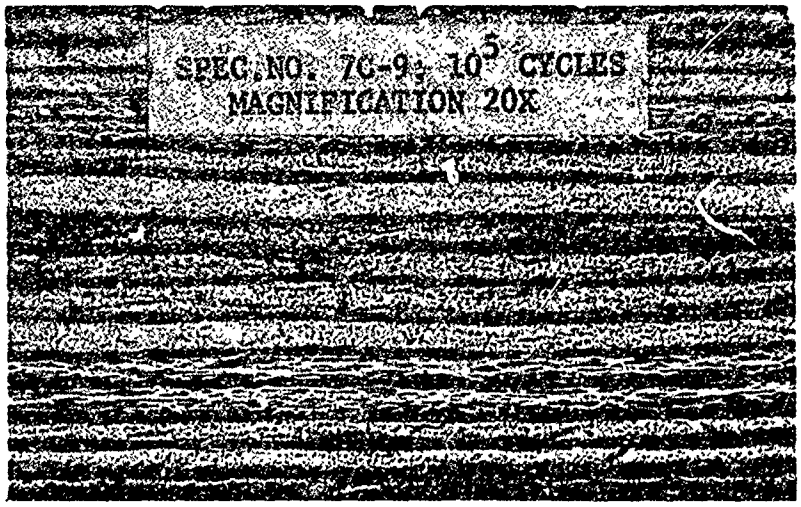
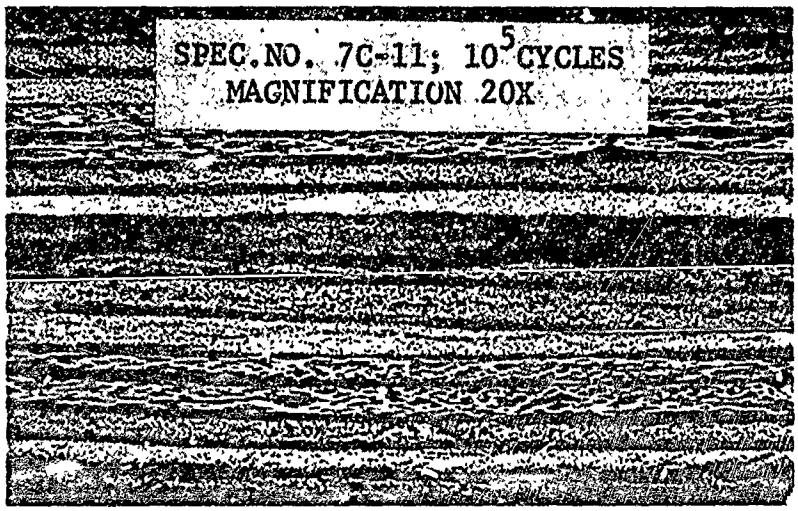


FIG. A-5 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 0°/ ± 45°/90° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 210 LBS), ROOM TEMPERATURE, DRY.





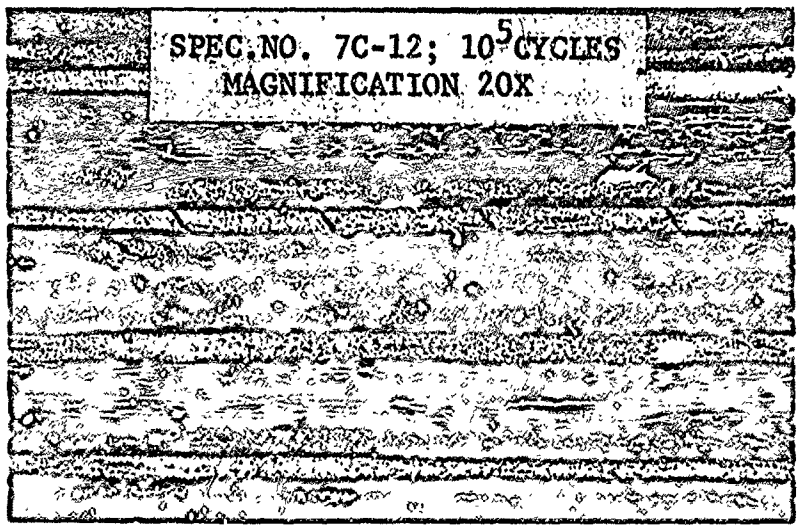
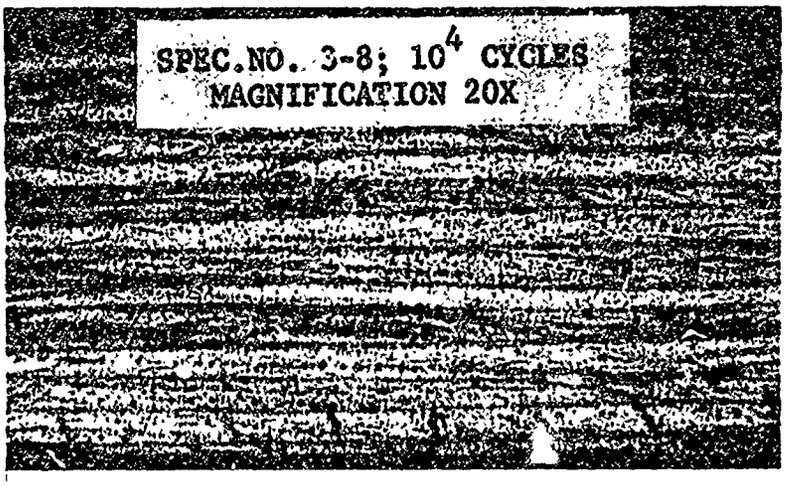
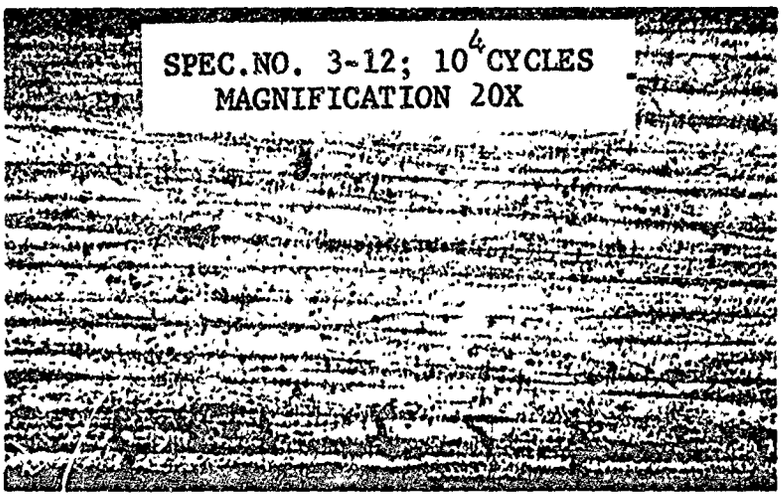


FIG. A-6 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 0°/ ± 45°/90° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 210 LBS), ROOM TEMPERATURE, DRY.





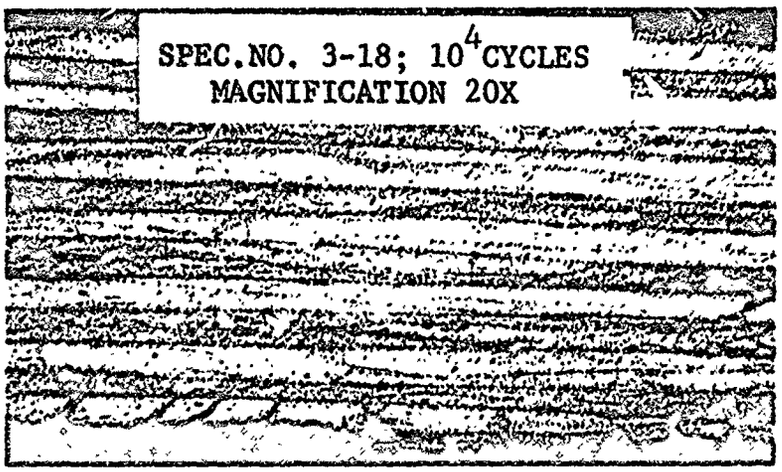
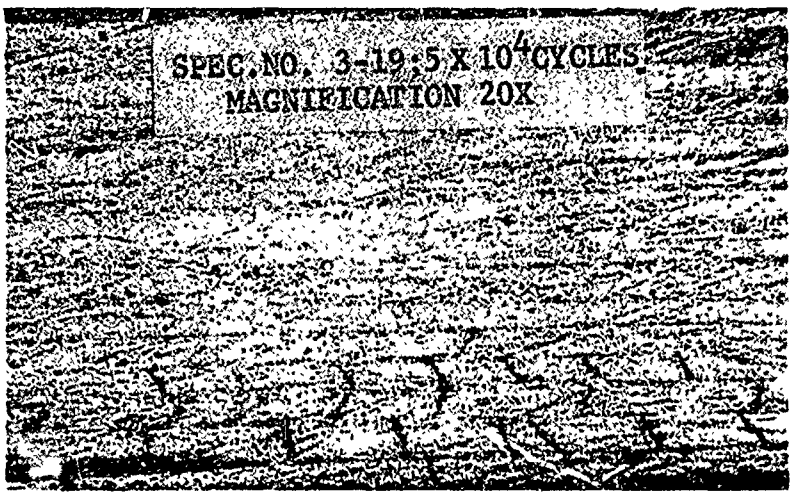
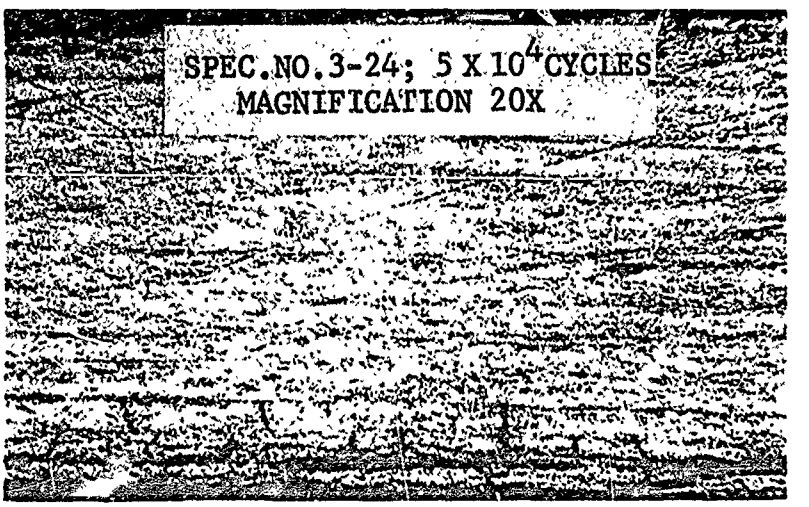


FIG. A-7 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 168 LBS), ROOM TEMPERATURE, DRY.





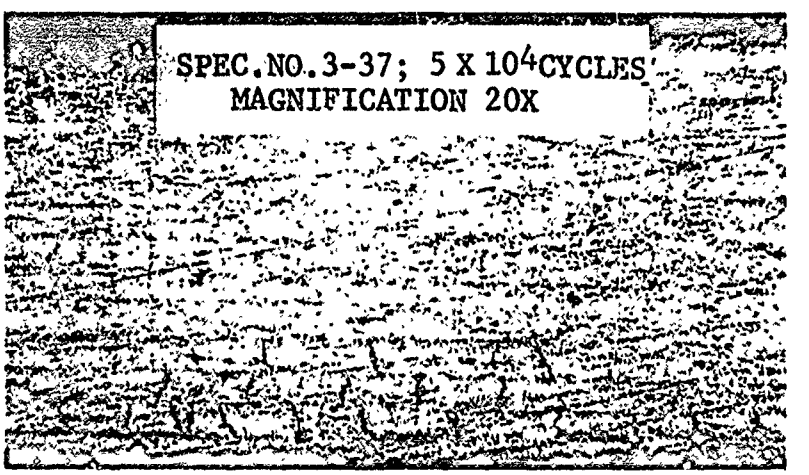
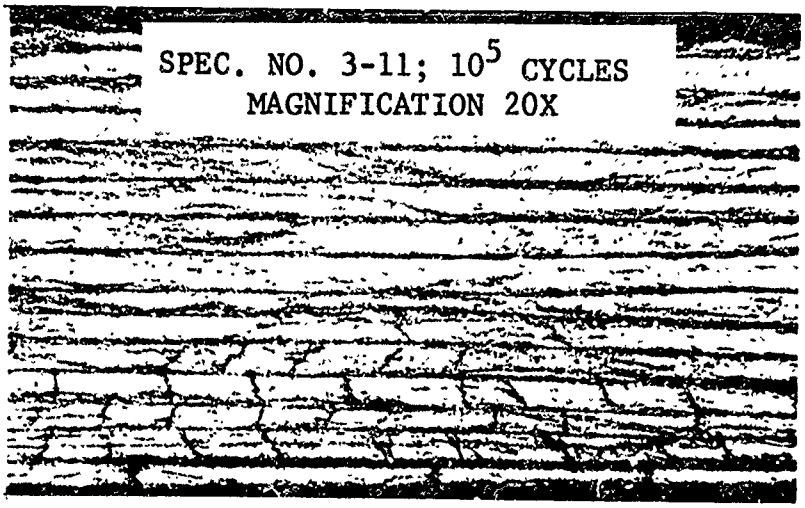
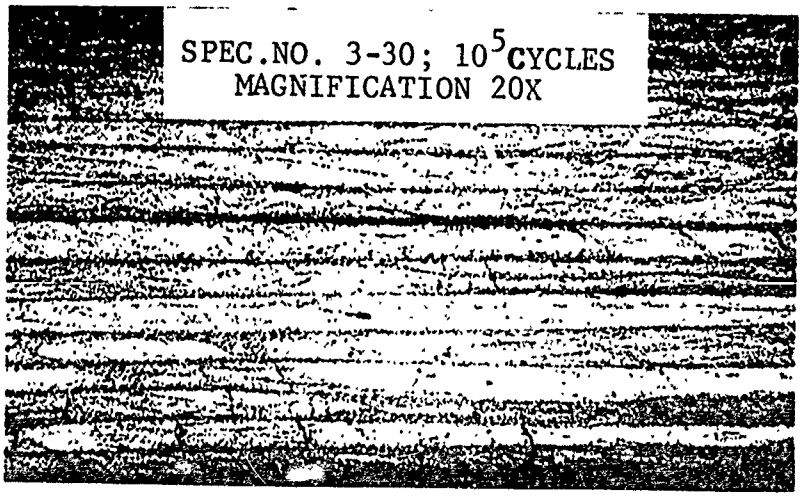


FIG. A-8 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 168 LBS), ROOM TEMPERATURE, DRY.





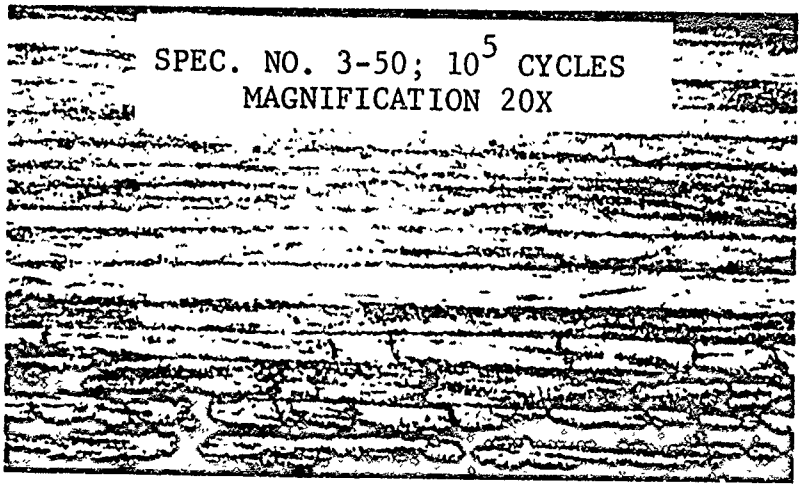
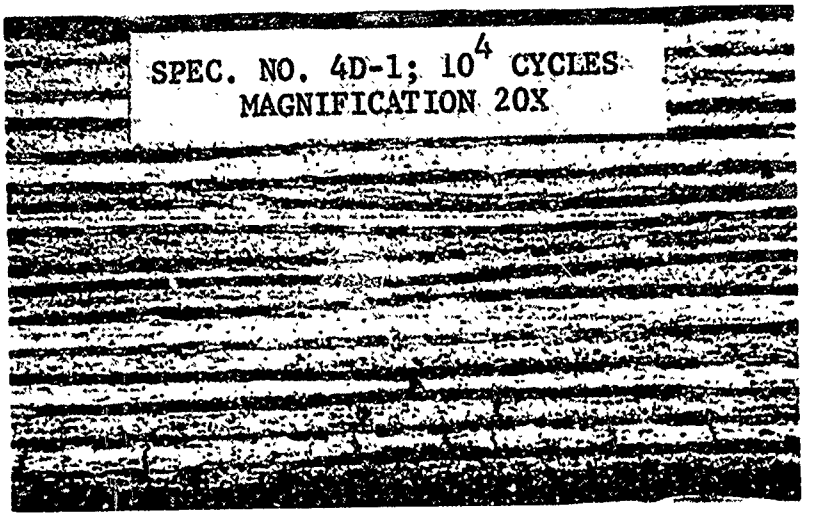
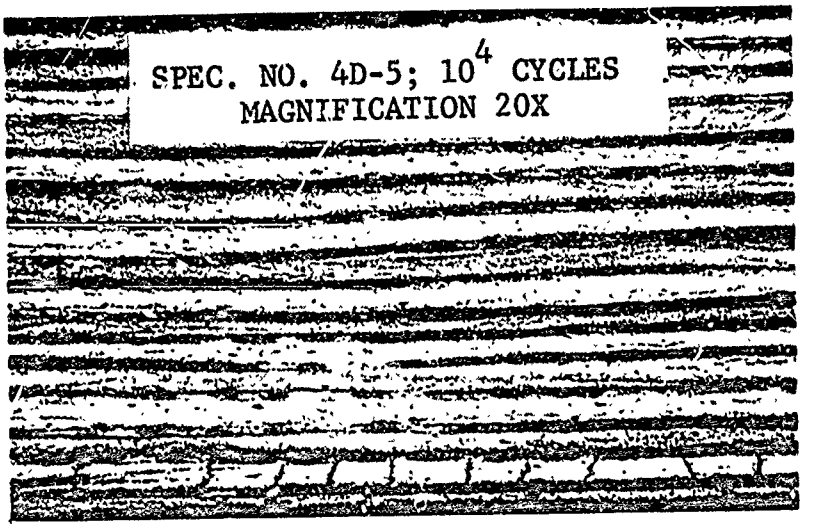


FIG. A-9 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 168 LBS), ROOM TEMPERATURE, DRY.





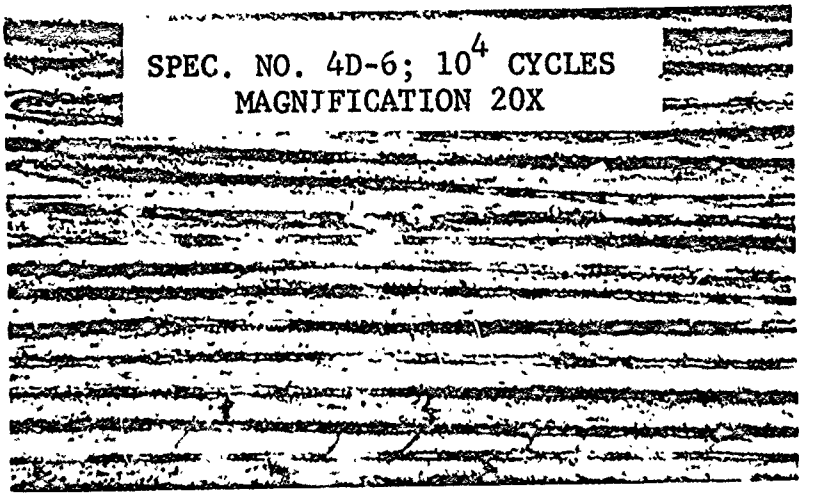
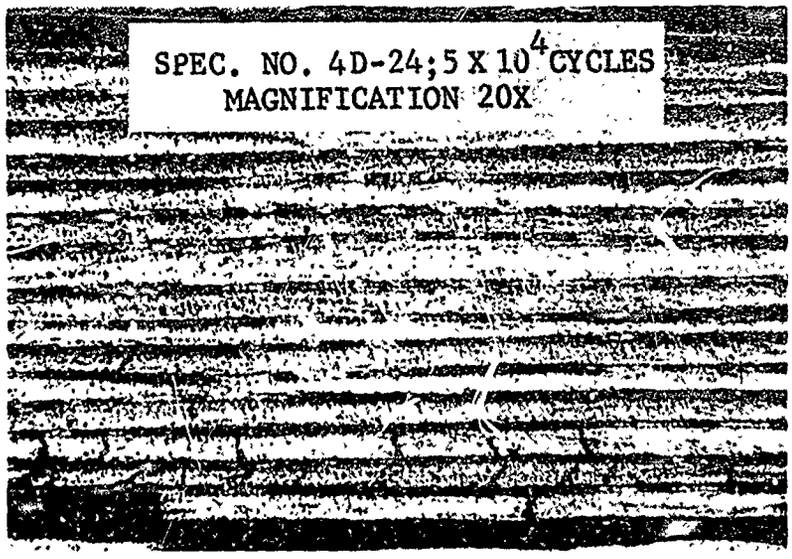
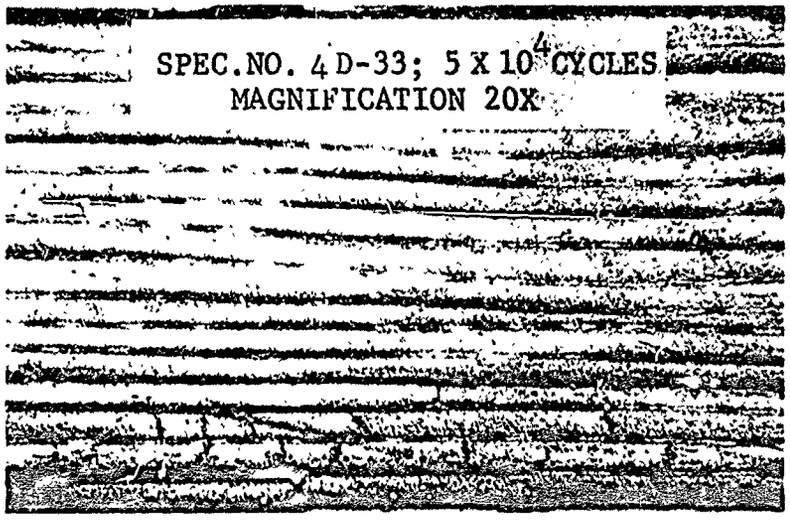


FIG. A-10 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 174 LBS), ROOM TEMPERATURE, DRY.





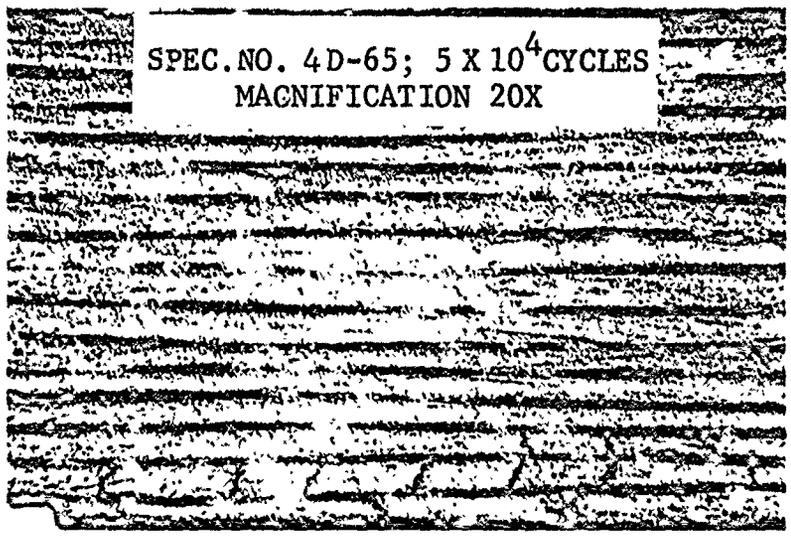
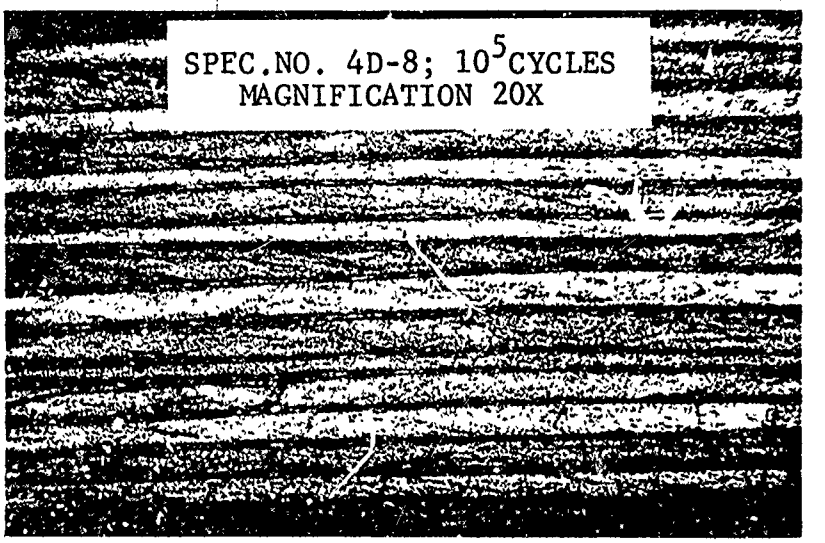
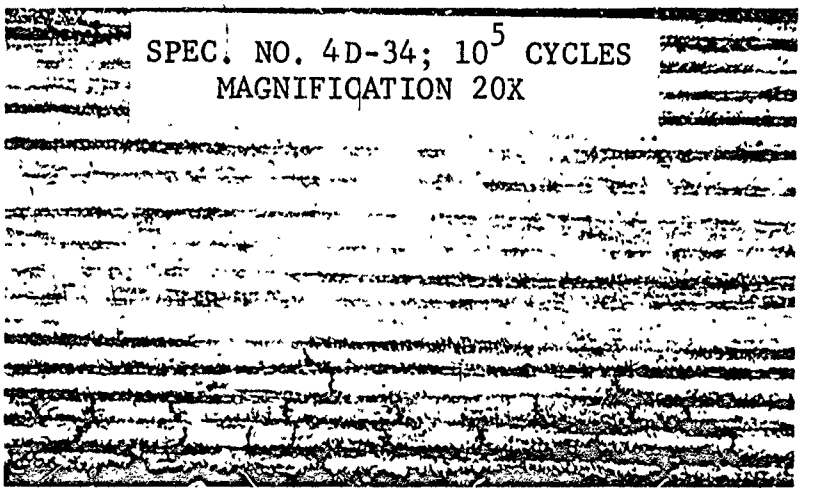


FIG. A-11 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 174 LBS), ROOM TEMPERATURE, DRY.





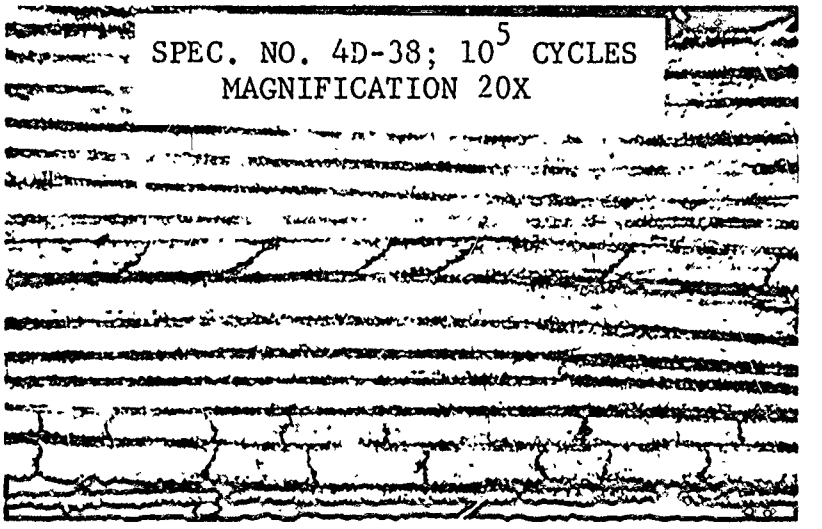
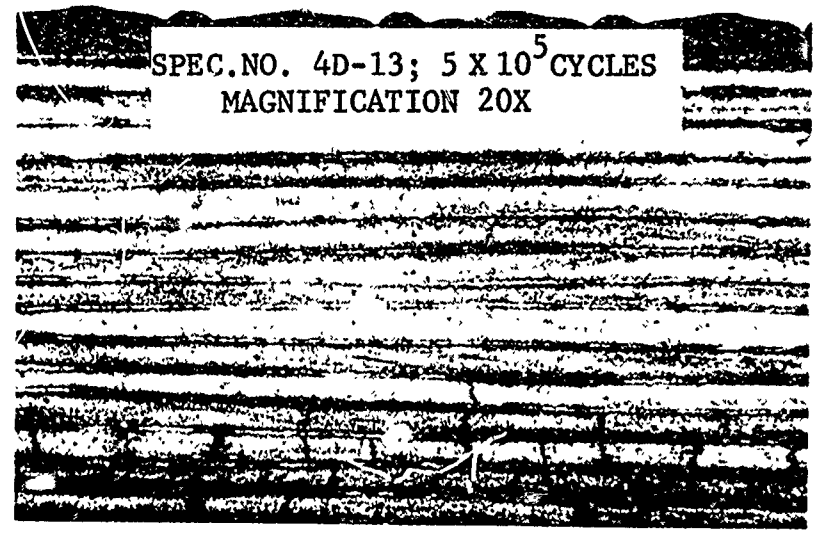
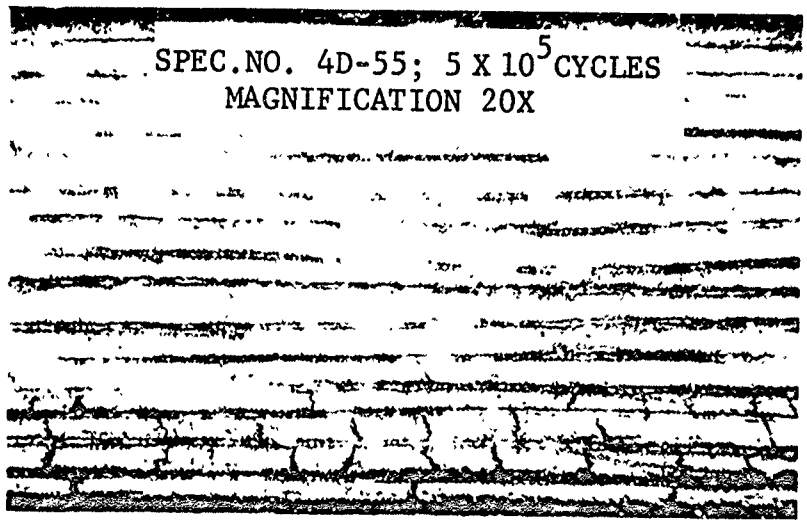


FIG. A-12 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 174 LBS), ROOM TEMPERATURE, DRY.





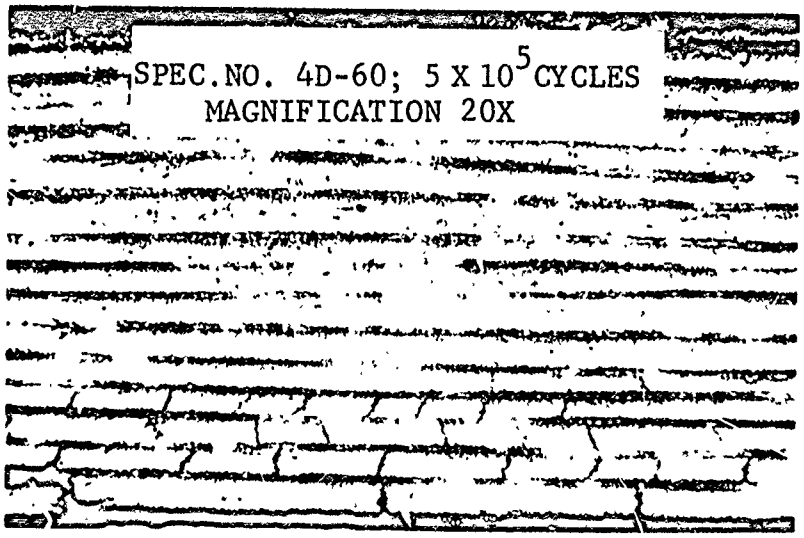
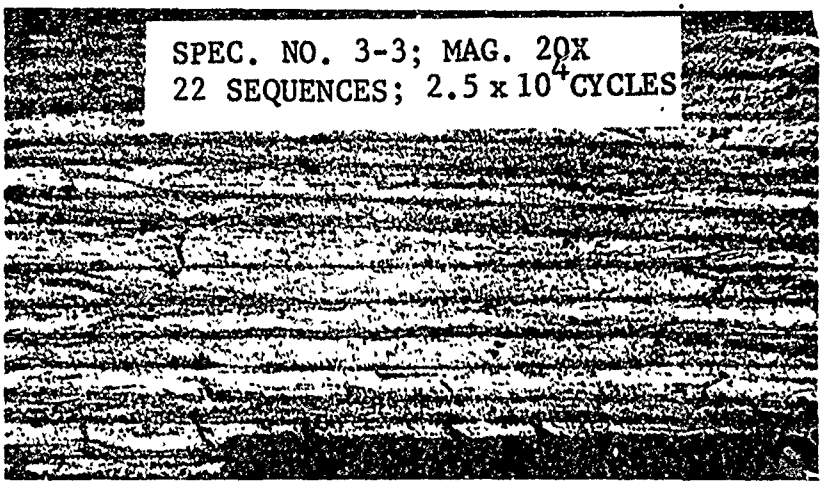


FIG. A-13 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°/135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE STRESS CYCLES AT R = 0.1 (MAX. LOAD/CYCLE = 174 LBS), ROOM TEMPERATURE, DRY.

APPENDIX B

PHOTOMICROGRAPHS OF GRAPHITE/EPOXY COMPOSITE SPECIMENS SUBJECTED TO VARIOUS SPECTRUM FATIGUE LOAD CYCLING



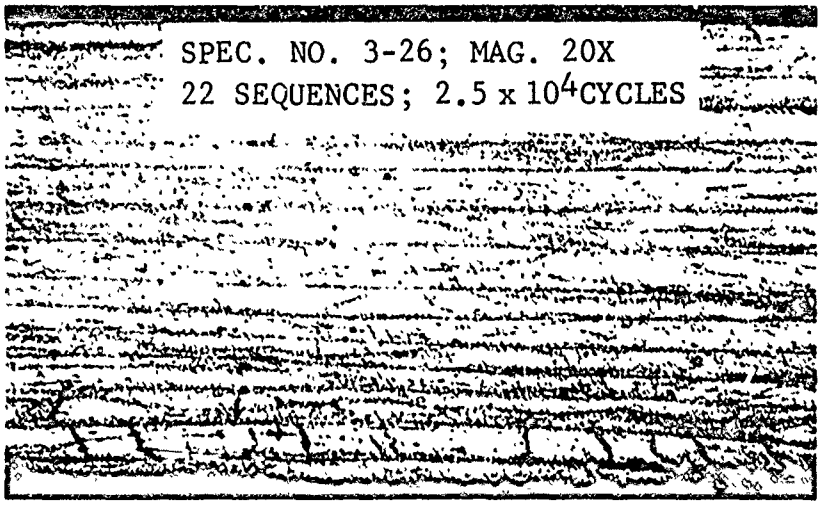
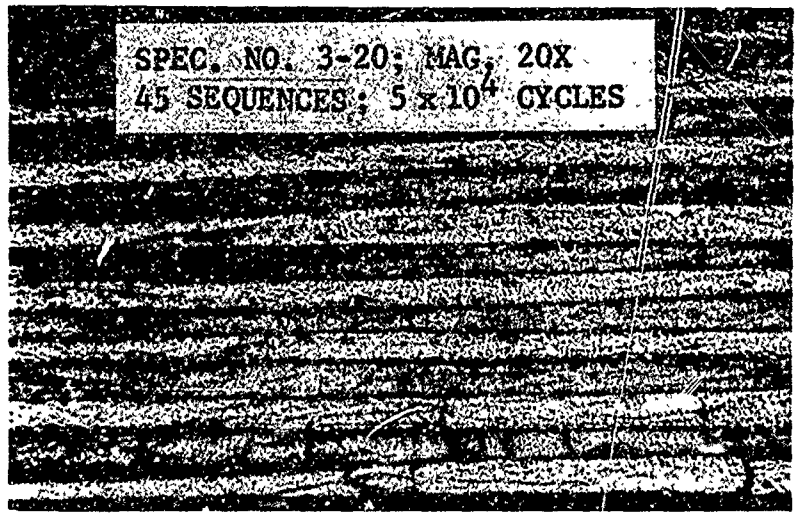


FIG. B-1 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°, 135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE



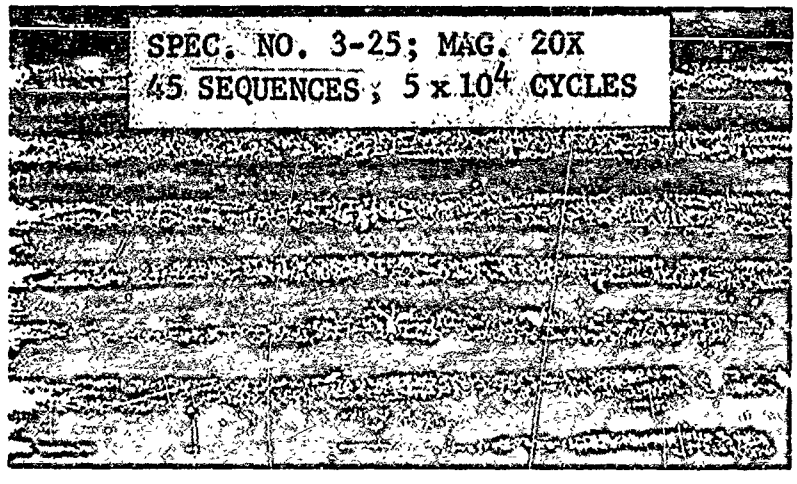
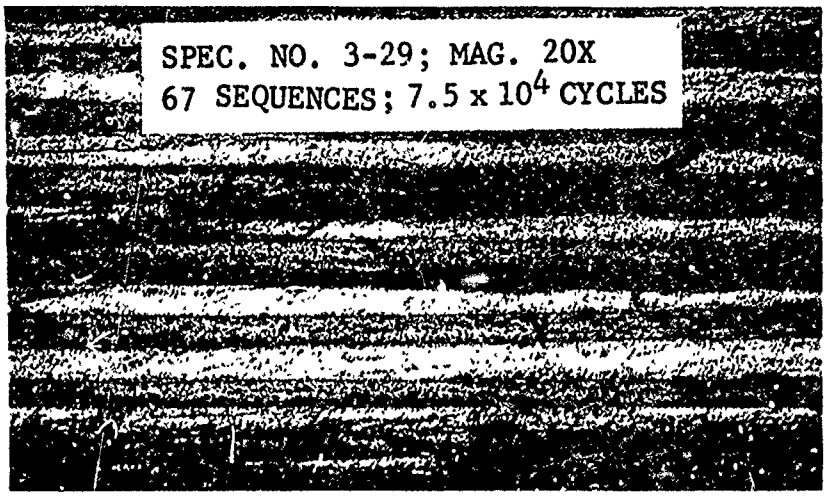
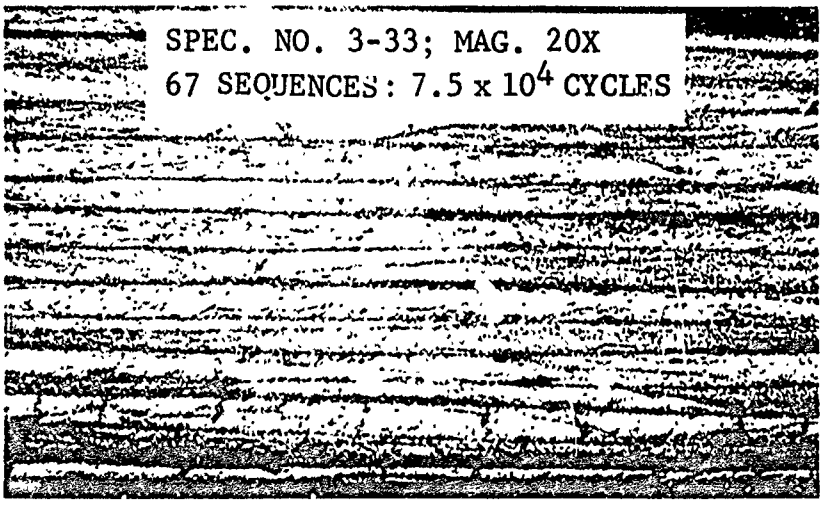


FIG. B-2 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°, 135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE





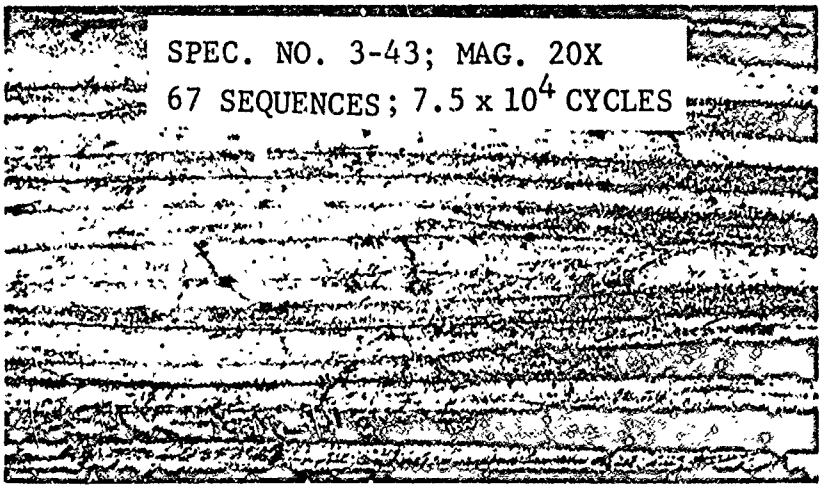
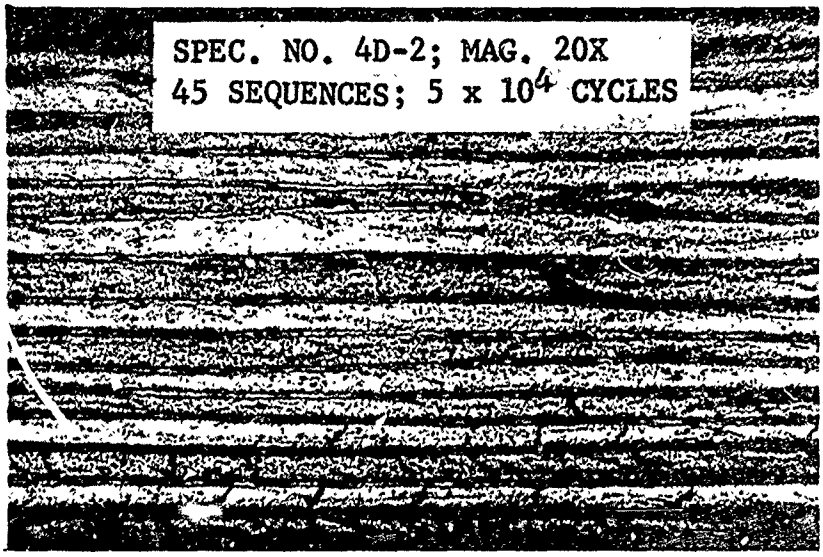


FIG. B-3 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°, 135° COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE



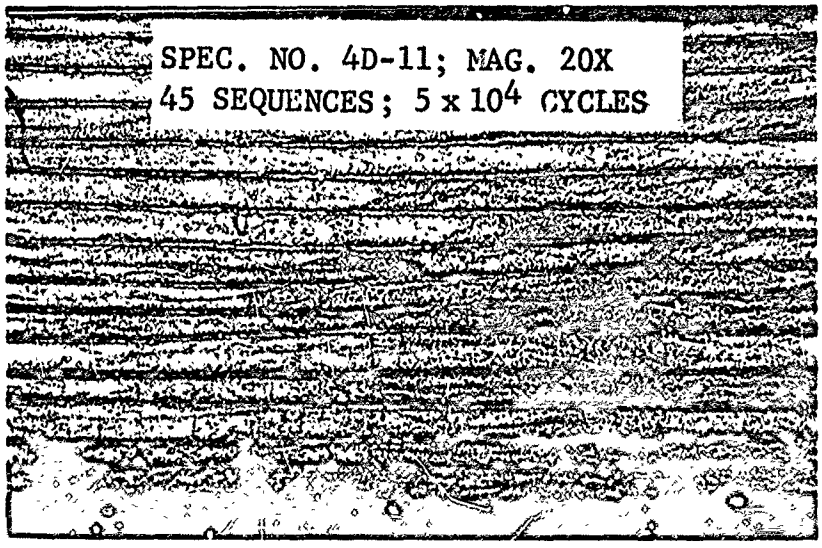
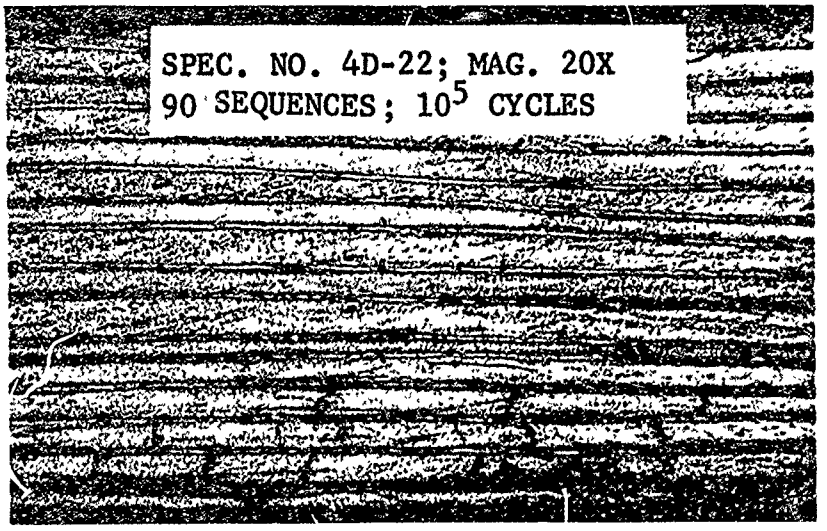
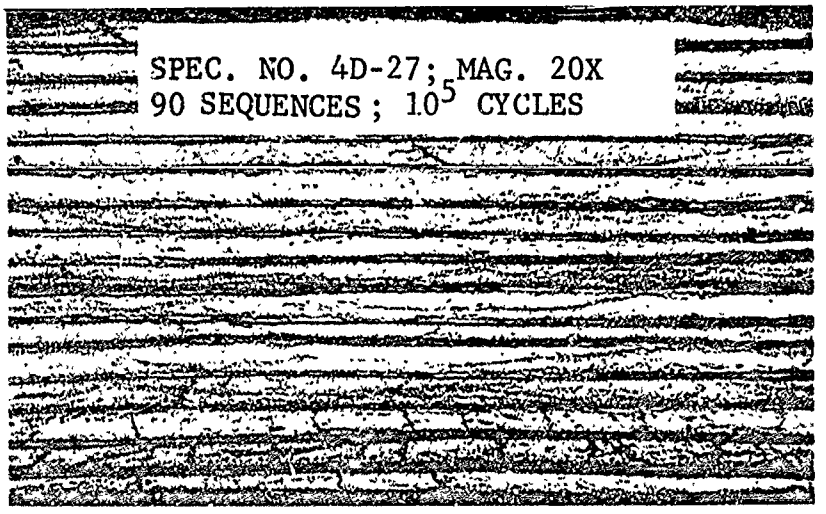


FIG. B-4 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°, 135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE





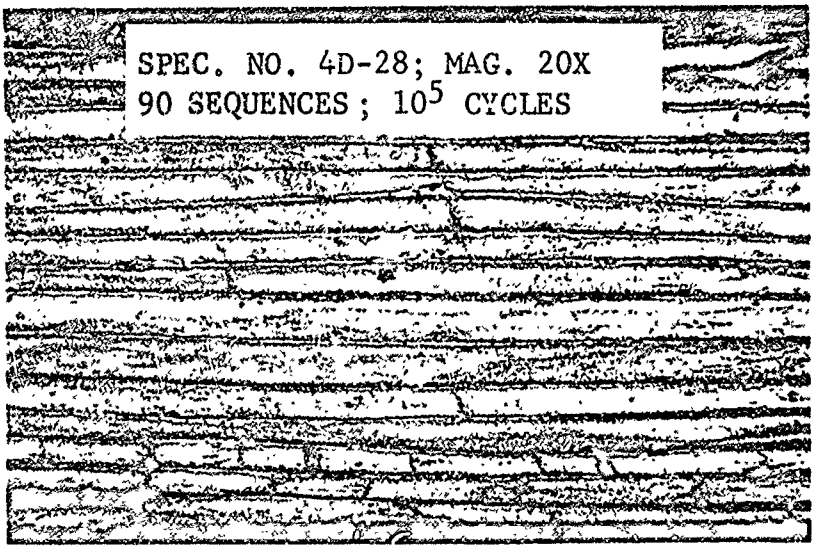
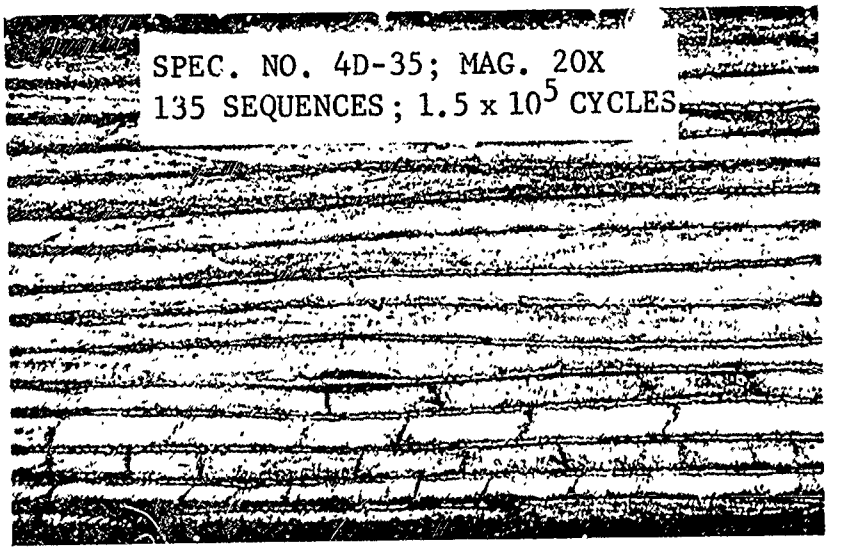
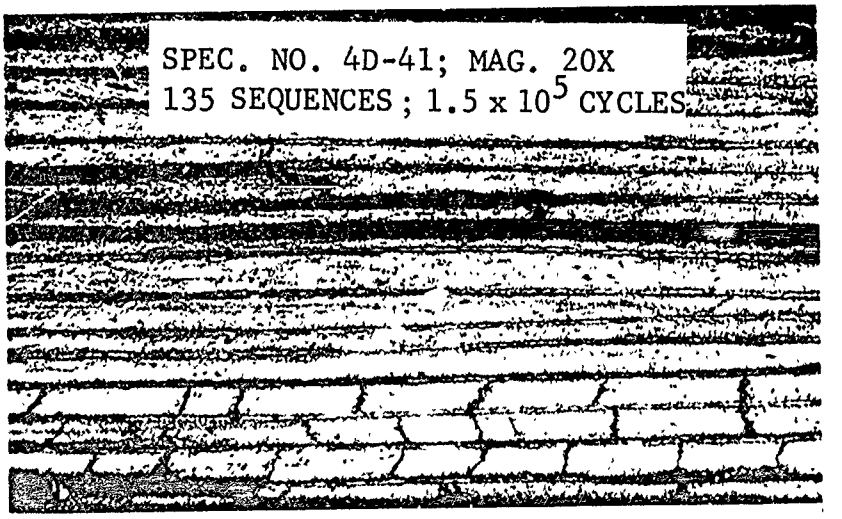


FIG. B-5 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°, 135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE





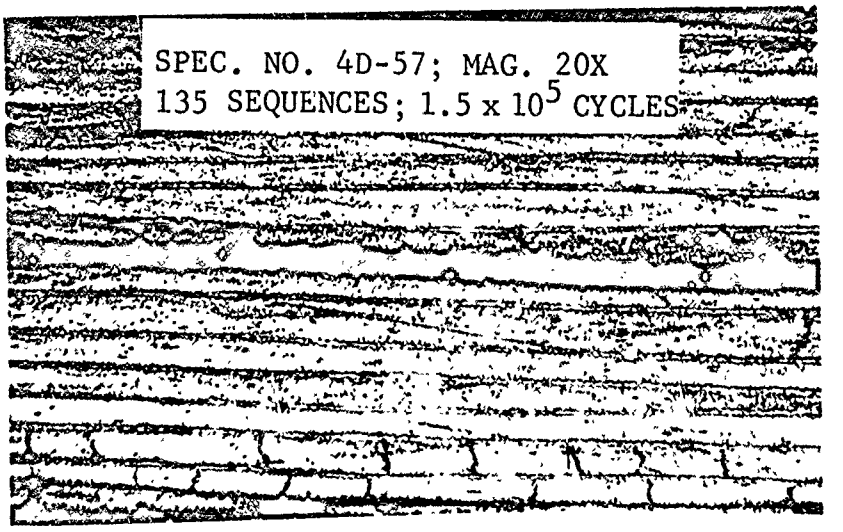


FIG. B-6 CROSS SECTIONAL PHOTOMICROGRAPHS OF MODMOR II/NARMCO 5206 PREPREG 16 PLY - 45°, 135° (WITH SCRIM CLOTH) COMPOSITE CANTILEVER BEAM SPECIMENS SUBJECTED TO VARIOUS FATIGUE (R = 0.1) LOAD SEQUENCES AT ROOM TEMPERATURE

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2. Rao, P. N. and Hofer, K. E., "Investigation of the Influence of Material Variables of Fatigue Mechanisms in Composites." Final Report December 1970, Department of the Navy, NASC Contract No. 00019-70-C-0378.

3. Broutman L. J. & Sahu, S. "Progressive damage of a glass reinforced plastic during fatigue" Proc. 24th Annual Technical conference, Society of the Plastics Industry Inc., 1969.

4. Forest, J. D. and Schaefer, W. H., General Dynamics, Convair Division "Advanced Composite Applications for Spacecraft and Missiles", AFML sponsored Project F33615-70-C-1442 Progress Report No. 3, December 1970.

5. Shockey, P. D., and Howeth, M. S., "Advanced Composite Technology Fuselage program AFML sponsored project, General Dynamics, Convair Division, 9th quarterly progress report, August, 1971.

6. Lubin, G. and August. A. "Repair Technology for Boron Epoxy Composites" AFML Project 33615-69-C-1498, Grumman Aerospace Corporation Eighth quarterly report, July, 1971.