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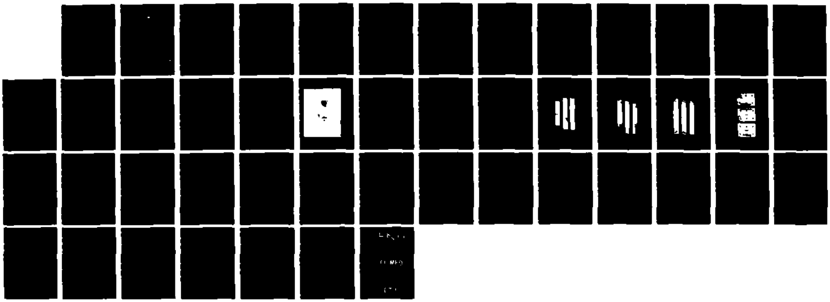

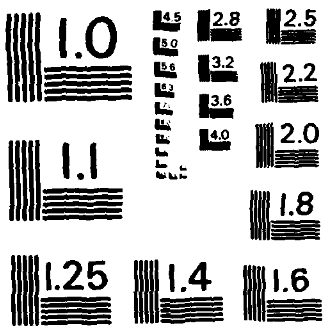

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FATIGUE PROPERTIES OF MULTIDIRECTIONAL BRAIDED COMPOSITES

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The fatigue performance of graphite/epoxy composites manufactured using a general braiding process was evaluated. Two styles of braided composites were fabricated and tested. Style I was the basic (1 x 1) braid pattern. Style II was constructed by holding half of the yarns as straight columns and braiding the rest of the yarns about the fixed yarns. Performance was compared to a 24 ply conventional laminate. Tension-tension, compression-compression and fully reversed constant amplitude fatigue tests were performed. Both style braids exhibited similar behaviour, except style II had longer compression-compression fatique life. As expected, in all fatigue conditions the braids had shorter lives than the baseline laminate. Non-the-less, the fatigue threshold stress levels observed for the braids as a percent of ultimate strength were similar to current laminated construction design stress values. Mechanical and impact properties for these materials have been previously reported in Report No. NADC-84030-60

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FOREWORD

This report presents the fatigue and shear properties for two styles of "Magnaweave" braided composites. Static-mechanical and impact properties were presented in Report No. NADC-84030-60. All testing was performed at the Naval Air Development Center. This effort is part of the "Airframe Structural Mechanics" work unit being performed for the Naval Air Systems Command. Dr. Daniel Mulville (AIR-310B) is the Structures Technology Administrator. Test specimens were purchased from the Cumagna Corporation who contracted the actual fabrication to Atlantic Research Corporation. The authors gratefully acknowledge the contribution to this research program of the following individuals: Dr. R.A. Florentine of Cumagna Corporation, Mr. R.T. Brown of Atlantic Research Corporation, and Mr. M. Corrigan and D. Krieger of the Naval Air Development Center.

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INTRODUCTION

Further structural performance improvements using filament-reinforced composite materials are limited by the low short-transverse strength, impact resistance, and delamination tendencies of conventional laminated construction. Since all the fibers of a laminate are oriented in-plane, only the relatively weak epoxy matrix is available to resist any out-of-plane loading. Thus, laminates have proven to be easily damaged by hard object impacts, such as dropped tools.

Further, once damage is created, the epoxy interface bonding the individual plies together provides little resistance to additional damage growth. A number of approaches are available to enhance the performance of graphite/epoxy laminates. These include tough resins, stitching, hybrids, third-phase inclusions, and multi-dimensional weaves. This report focuses on a class of multi-dimensional weaves.

A general braiding process has recently been proposed which achieves a fully-integrated fiber structure and allows the automated braiding of complex shapes, such as I-beams, hat sections, and cylinders.(1 to 3) Fibers are loaded on yarn carriers mounted on an orthogonal braiding bed. Each carrier moves in a predetermined path about the bed, resulting in a continuously intertwined fiber structure. This reinforcement network contains no weak ply interfaces along which damage can propagate. The presence of "through-the-thickness" fiber reinforcement locks the composite together inhibiting impact damage. This irregular orthogonal-braiding process has been referred to by various names, including "Magnaweave"(1) and "Through-The-Thickness Braiding."(4). It is an extension of the General Electric "Omniweave" concept. Another method to achieve a similar fiber structure is the Adjacent Yarn Position Exchange (AYPEX) braiding process invented at the Naval Surface Weapons Center.(5)

The static mechanical and impact properties of graphite/epoxy composites manufactured using the "Magnaweave" process were obtained in a previous study(6) and are summarized here.

---

(1)Florentine, Robert A., "Integrally-Woven Complex Shapes for Multidimensionally Reinforced Composites," presented at the 13th National SAMPE Technical Conference, October 13–15, 1981.

(2)Ko, Frank K., "Three-Dimensional Fabrics for Composites, An Introduction to the Magnaweave Structure," presented at the International Conference on Composite Materials, Tokyo, Japan, 1982.

(3)Macander, A.B., Crane, R.M., and Camponeschic, E.T., Jr., "Fabrication and Mechanical Properties of X-D Braided Composite Materials," presented at the 7th Symposium on Composite Materials Testing and Design, Philadelphia, Pennsylvania, 2–4 April 1984.

(4)Brown, R.T., "Application of Through-the-Thickness Braiding Technology," presented at the Fiber Society/SAMPE Conference on High Performance Textile Structures, Philadelphia College of Textiles and Science, Philadelphia, Pennsylvania, 6–8 June 1984.

(5)Weller, R.D., "Three dimensional interbraiding of composite reinforcements by AYPEX," Report No. NSWC TR 84-378, in preparation.

(6)Gause, L.W. and Alper, J.M., "Mechanical Properties of 'Magnaweave' Composites," Report No. NADC-84030-60, December, 1983.

Two styles of braided test coupons were fabricated and tested. Style I is the basic (1 x 1) braid pattern. Style II is constructed by holding half of the yarns as straight columns and braiding the rest of the yarns about the fixed yarns. This style is designatated (1 x 1)½ fixed. Celion 12000 carbon fibers were used to braid preforms roughly 5 x 30 inches, which were impregnated with Hercules 3501-6 expoxy resin and autoclave cured. Individual test coupons were then machined from the cured panels. Some difficulties were encountered developing the processing methods to vacuum draw the hot melt resin into the fiber preform and obtain a uniform composite upon cure. As a result, there was a large variation in finished composite thickness and fiber volume. Average fiber volume for the Style I specimens was 53.9 percent. Style II achieved a fiber volume average of 55.8 percent. Measurement of apparent braid angle from the surface of each specimen also showed large variations between coupons. The average braid angle was 19.4° for Style I and 23.1° for Style II. The overall quality of the specimens was, nonetheless, adequate for this initial characterization study. Processing difficulties encountered should be easily eliminated with manufacturing experience. A conventional 24 ply AS1/3501-6 graphite/epoxy laminate with $(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)S$ *stacking sequence was tested concurrently* to provide a baseline for structural performance comparisons. Results of static testing showed that Style I behaves similarly to a $(\pm 20)S$ angle-ply and Style II is similar to a $(\pm 20/0_2)_S$ laminate. Tests performed on braided specimens with ¼ inch diameter open holes show no tensile strength reduction due to the hole. Bearing strength, transverse strength, and transverse stiffness properties are lower than laminated composites. Dropped-weight instrumented impact tests were used in conjunction with ultrasonic C-scan inspection to characterize the impact response and determine damage gradients over the entire range of damage from incipient level up through complete penetration of the composites. Results show the braid greatly limits the extent of impact damage but does not increase the impact damage threshold. This report completes the initial structural property characterization of these braids by assessing their fatigue and in-plane shear properties.

EXPERIMENTAL PROCEDURE

MATERIAL

The two styles of braided graphite/epoxy composites discussed above were evaluated in fatigue, shear, bolt bearing, and shearout and compared to a conventional laminate baseline. Details of the braided composite manufacturing are given in reference (6). It was assumed prior to fabrication that the in-plane fiber directions of Style I would be approximately $\pm 45°$ and the mechanical properties would be similar to a $\pm 45°$ symmetric angle ply. Style II was chosen, assuming the in-plane fiber directions would be approximately 0° and $\pm 45°$ to simulate a *typical fiber-dominated laminate found on aircraft* structures. For comparison, a baseline laminate was chosen that is a typical fiber-dominated laminate. The baseline laminate was manufactured from AS1/3501-6 prepreg and autoclave cured.

Stacking sequence for the 24 ply laminate was: $(\pm 45/0_2/\pm 45/0_2/\pm 45/0/90)_S$

Target thickness for all specimens was 0.125 inch.

All specimens were both visually and ultrasonically inspected prior to testing. No anomalies were noted in the baseline laminates and baseline specimens were uniformly consistent. Large variations were noted, however, in both style braids. Visual inspection revealed a noticeable texture or waviness on the surface of each specimen. Measurement of the apparent braid angle θ (which is measured in-plane with respect to the 0° axis) on the surface of each specimen showed both styles achieved a braid angle much less than the originally expected 45°. Average braid angle for the Style I coupons tested for this report was 17.1°; Style II averaged 23.9°. Apparently, the braid angle is not as easy to control during manufacturing as was assumed. Average specimen thickness and fiber volume for Style I specimens was 0.1229 inch and 59.1 percent, respectively, and Style II yielded 0.1477 inch and 59.1 percent.

TEST PROCEDURE

TEST PLAN

Table 1 shows the test plan established to evaluate the behavior of this new material system in fatigue, shear, bolt bearing, and shearout. Individual test coupon geometries are presented in figures 1 through 5. All tests were performed in an M-T-S closed-loop servo-hydraulic test machine equipped with "Alignomatic" self-aligning hydraulic grips. Tests were performed in a controlled environment nominally maintained at 72°F and 35-40% R.H.

FATIGUE TEST

The fatigue portion of the test plan (table 1) was established to screen the fatigue performance of new material systems proposed for aircraft structural applications. Test specimen replicates were selected to provide economy in testing while still providing adequate numbers for statistical comparisons. Five replicate constant amplitude fatigue tests were performed at each of three load levels to establish individual S-N curves. Load levels were selected based upon the static test results and are chosen to correspond roughly to 10,000 cycle life, 100,000 cycle life, and to establish a fatigue endurance limit here defined as the stress corresponding to 1,000,000 cycle life. Specimens surviving 10^6 cycles were residual strength tested. A cycle rate of 5 Hz was chosen to minimize the effects of specimen heating.

Since fatigue life can vary dramatically with stress ratio, $R = \frac{\text{minimum applied stress}}{\text{maximum applied stress}}$, S-N curves are generated for compression-compression (R=10), tension-tension (R=0.1) and tension-compression (R=-1) loadings to examine the performance of a new material over a broad range of stress ratios typically encountered in aircraft structure. Upper wing skins see primarily compressive loads, lower wing skins are tension dominated, and control surfaces, such as rudders, see a roughly equal tension-compression mix. These three S-N curves are the minimum necessary to expose any major abnormality in a new material's fatigue performance. Tension fatigue tests are sensitive to crack growth failure modes as typically seen in metals. Compression fatigue examines stability related failure modes, such as those seen in laminated composites where damage accumulates in the matrix, reducing its ability to support the fibers against buckling failure. This includes global buckling as a result of delamination and micro-buckling due to matrix shear resistance degradation and damage to the fiber/matrix bond. Tension-Compression fatigue explores any interaction between these various damage modes.

SHEAR TEST

Five replicates each of Style I, Style II, and baseline laminate were subjected to rail shear testing. A test specimen mounted for testing is shown in figure 6. The rail shear test method is based upon the diagonal-load-introduction bonded rail-test configuration of reference (7). The steel rails are bonded to the specimens with EA934 adhesive. Tensile loads are applied to the rail at a constant 0.01 inch/minute displacement rate until either load drops or catastrophic failure, whichever occurs first.

BOLT BEARING AND SHEAROUT TESTS

The bolt bearing and shearout tests of reference (6) were repeated because the test specimens used in the previous report had unusually low fiber volume fractions which may have resulted in the braids poor performance. A ¼ inch-diameter steel bolt is used to apply a tension type load (shearout) or compression type load (bearing) to the specimen. Specimens are ramp loaded at 100 lb/sec. until failure, here defined as initial yielding.

TEST RESULTS AND DISCUSSION

SUMMARY OF FATIGUE TESTS

Raw data sheets for all fatigue testing are included in appendix A. Figures 7, 8, and 9 present the S-N curves developed for $R = 0.1$, $R = -1$ and $R = 10$, respectively. Baseline laminate and both style braids results are plotted on each curve. The data is highly scattered and the trend-lines plotted on the curves are based on rough averages of the life at each stress level. The load axis intercepts are the average static strength values obtained from reference (6). Several specimens were monitored during testing with thermocouples to insure there was no cycle-rate related heating. Photographs of failed fatigue specimens are presented in figures 10, 11, and 12.

SUMMARY OF RAIL SHEAR TESTS

The shear moduli of the rail shear specimens are presented in table 2, and data on the individual specimens is available in appendix B. In all but three test cases, failure was due to either rail separation or failure through the bolt line so that no shear strength data was obtained. Photographs of typical failed specimens are presented in figure 13.

SUMMARY OF SHEAROUT AND BEARING TESTS

Bearing and Shearout test results are presented in table 3. Raw test data is included in appendix B.

DISCUSSION

Comparisons of fatigue performance between laminates fabricated with woven cloth to conventional tape layups generally show the cloth systems to have shorter lives. This is attributed to the fiber curvature or waviness intrinsic to the cloth structure which allows the fibers to bend in addition to deforming axially under load and so works the matrix more severly. Therefore, an eagerly awaited result here was how severe a fatigue penalty the braided material would suffer as a

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(7)Garcia, R., Weisshaar, T.A. and McWithey, R.R., "An Experimental and Analytical Investigation of the Rail Shear-test Method as Applied to Composite Materials," Experimental Mechanics, Vol. 20, No. 8, August, 1980.

consequence of the curvature associated with its fully integrated structure. In this respect, the Style II braid was expected to out-perform the Style I braid since the longitudinal fibers of the Style II, which primarily carry the load, were held as straight columns during braiding, whereas the load in the Style I had to be sustained by curving fibers oriented off the 0° axis.

Figures 14 through 16 show respectively the fatigue S-N curves with the maximum amplitude stress non-dimensionalized for tension-tension (T-T) compression-compression (C-C), and tension-compression (T-C) cases. The maximum amplitude stress is non-dimensionalized by the static ultimate tensile strength of each material for T-T fatigue and by the static ultimate compressive strength for each material for C-C and T-C fatigue.

Looking at the T-T results in figure 14, the baseline laminate exhibits a greater lifetime than the two braided styles at the same strength ratios. The two braided styles shown in this figure behave almost identically. Under C-C fatigue, the results are shown in figure 15. Again, the baseline laminate shows a greater lifetime when compared at the same strength ratio to both braided styles. Comparing the braided styles with each other, Style II shows greater life capability than Style I as the strength ratio decreases. At the lower ratios, the fixed 0° yarns in Style II provide greater resistance to catastrophic fatigue damage. Similar to the other two fatigue conditions, under T-C fatigue the baseline laminate showed a longer lifetime than either of the two braided styles, figure 16. Both braids behave almost identically.

It was shown in all three types of fatigue tests that the baseline laminate has a greater lifetime than either of the two braided styles at the same ratio of maximum amplitude stress to ultimate strength. Using the same ratio, both braided styles behave similarly under T-T and T-C fatigue. However, under C-C fatigue, Style II shows greater lifetimes at the lower ratios.

To assess the overall fatigue performance of these materials, a fatigue threshold stress level will be defined as that stress on the S-N curve corresponding to 1,000,000 cycle life. These values are presented in table 4. It is clear that on both a gross stress basis and a normalized percent of ultimate stress basis, the laminate is superior to the braids under all load cases. But the critical question is whether this matters in the context of a design.

Fatigue is not a design constraint in laminated composite structures. Knockdown factors imposed on graphite/epoxy to compensate for humidity, temperature effects, and possible impact damage restrict its design strain level to 4000 μ in/in (approximately ⅓ of tensile ultimate), far below the laminates fatigue threshold stress and well within the braids fatigue capability. Indeed, we would expect the same design strain levels to be imposed on the braids as are used with the laminates. Both are limited by the epoxy matrix's poor hot-wet strength, even though the braid may tolerate damage better.

Results from the rail shear testing in table 2 showed that the shear modulus for both braid styles and the baseline laminate are consistent with those calculated in reference (6) using a simple laminate analysis analogy. This analogy seems reasonable to use as an initial estimate of the modulus since, as was shown in reference (6), the fibers travel through the thickness of the specimen at a very shallow angle.

Results from the bearing and shearout tests are shown in figure 17 compared with the results from reference (6). While the new test values (specimens with greater fiber volume) show a slight improvement over the previous results, the braids still performed at only half the strength of the baseline laminate. Inherent to the braided composite is small resin rich pockets throughout the structure. The existence of these pockets near the hole would account for the low yielding strength.

CONCLUSIONS AND RECOMMENDATIONS

- Under tension-tension and tension-compression constant amplitude fatigue testing, both braided styles exhibit similar behavior.
- Under compression-compression constant amplitude fatigue testing, Style II (with 50 percent of the fibers fixed in the 0° direction) has a longer lifetime than Style I.
- In all three fatigue conditions, T-T, T-C, and C-C, the baseline laminate has a greater lifetime than either of the braided composites. Nonetheless, the fatigue threshold stress levels observed for the braids as a percent of ultimate strength are comparable to current laminated construction design stress values.
- Braided composites have a low yield strength when loaded through a drilled hole.
- A good estimate of the in-plane shear modulus can be made using a laminate analysis analogy.
- The effects of damage on braided composite fatigue life needs to be determined. Of particular interest are the effects of an open hole on the tensile fatigue life of braids in light of their apparent notch-insensitivity, observed during static testing.
- All tests performed here were at room temperature on dry specimens. The influence of moisture and temperature on the static and fatigue properties of the braids needs to be addressed.

TABLE 1

TEST PLAN

TEST DESCRIPTION		# SPEC.	GEOMETRY
FATIGUE			
TENSION-TENSION	R = .1	15	9" x 1"
TENSION-COMPRESSION	R = -1	15	8" x 1"
COMPRESSION-COMPRESSION	R = 10	15	8" x 1"
RAIL SHEAR G_{12}		5	5" x 3.5"
SHEAROUT (TENSION) $\sigma_{br}{}^{t}$		5	4.5" x 1"
BEARING (COMPRESSION) $\sigma_{br}{}^{c}$		5	2.5" x 1"

TABLE 2

SHEAR MODULUS G_{12} (MSI)

	EXPERIMENTAL MEAN-VALUE	C.V.	PREDICTED VALUE (6)
24 PLY AS/3501 (42/50/8)	3.04	32.0%	2.6
C12000/3501 (1x1) BRAID	1.87	13.5%	2.4
C12000/3501 (1x1)½ FIXED	1.84	25.0%	1.5

TABLE 3

BOLT BEARING AND SHEAR-OUT TEST RESULTS

	C12000/3501 (1 X 1) BRAID		C12000/3501 (1 X 1) ½ FIXED	
	MEAN	C.V.	MEAN	C.V.
F_{br}^{C} KSI (D = .25 in)	54.1	12.6%	57.5	10.1%
F_{br}^{t} KSI (D = .25 in) e/D = 2.5	35.5	7.8%	39.8	31.5%

TABLE 4

FATIGUE THRESHOLD STRESS, σ_{TH}

$\sigma_{TH} \Rightarrow N = 1,000,000$

		24 PLY AS/3501 (42/50/8)	C12000/3501 (1 X 1) BRAID	C12000/3501 (1 X 1)½ FIXED
TENSION FATIGUE R = .1	(KSI)	98.0	55.0	61.0
	$\% \sigma_1^{tu}$	74%	57%	56%
REVERSED FATIGUE R = −1	(KSI)	30.5	21.5	25.0
	$\% \sigma_1^{cu}$	50%	35%	36%
COMPRESSION FATIGUE R = 10	(KSI)	48.0	27.3	38.0
	$\% \sigma_1^{cu}$	79%	44%	55%

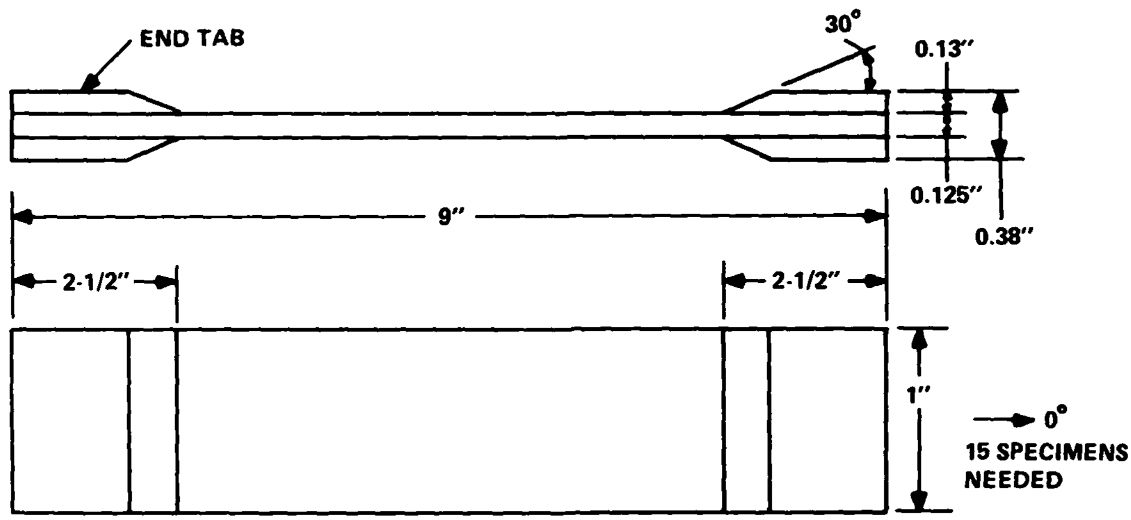

Figure 1. Tension Fatigue Specimen

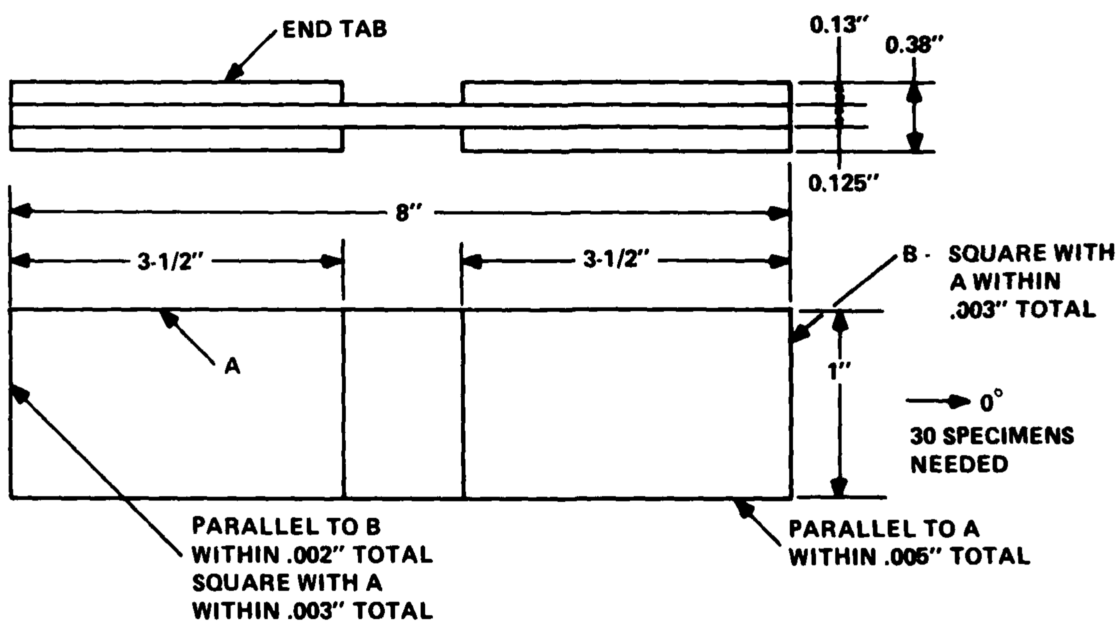

Figure 2. Compression and Reversed Load Fatigue Specimen

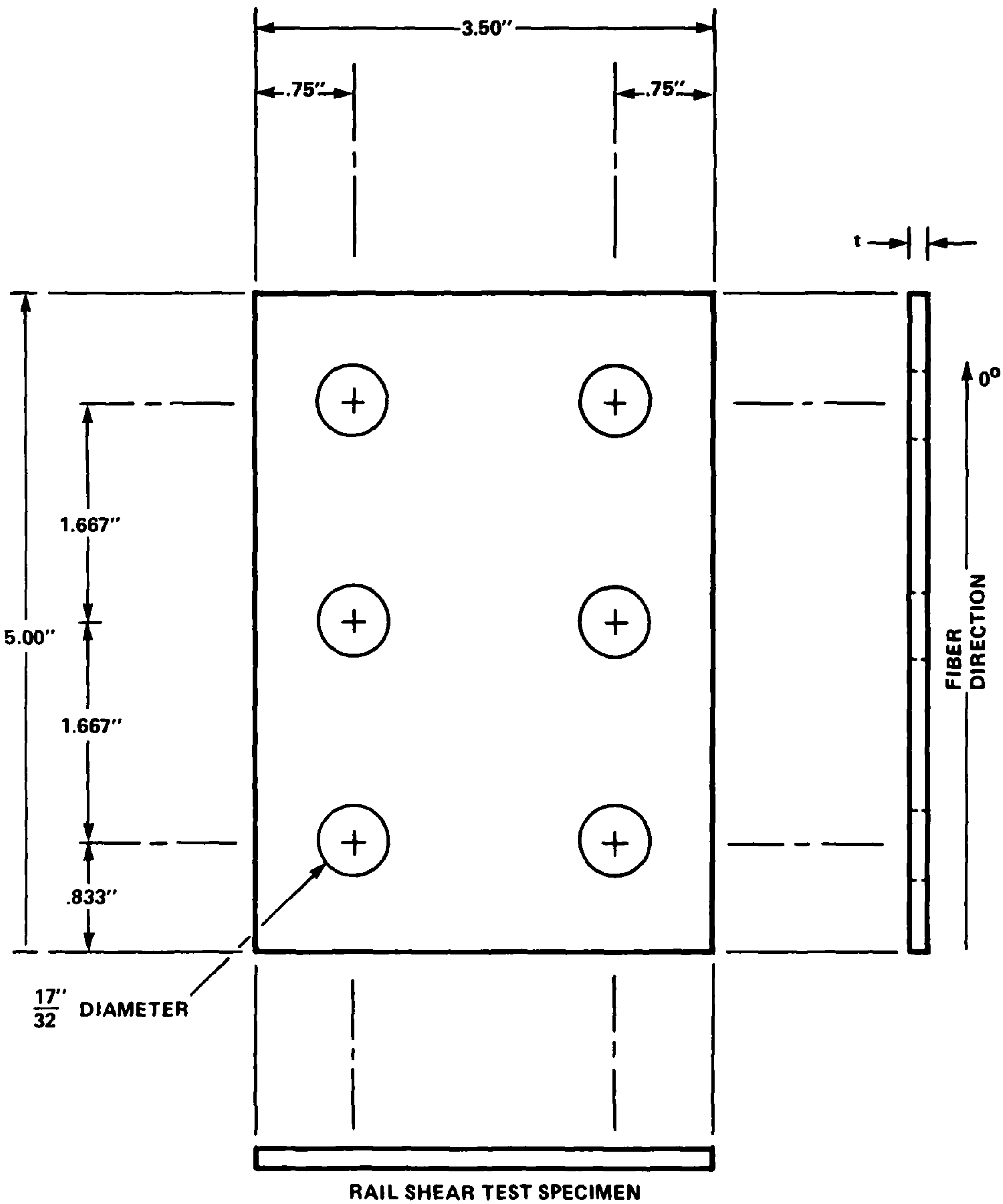

Figure 3. Rail Shear Specimen

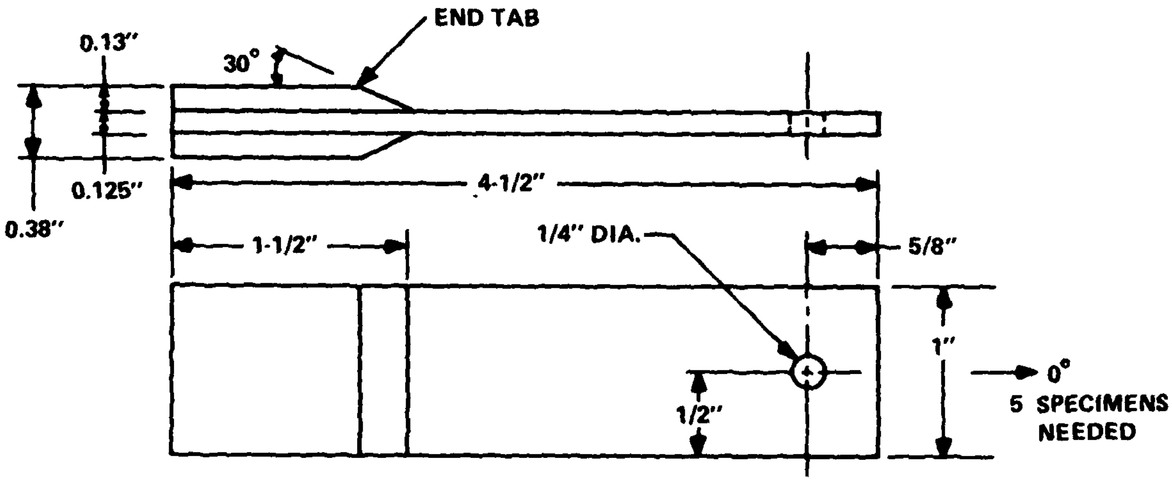

Figure 4. Shearout Specimen
(Tension Loading)

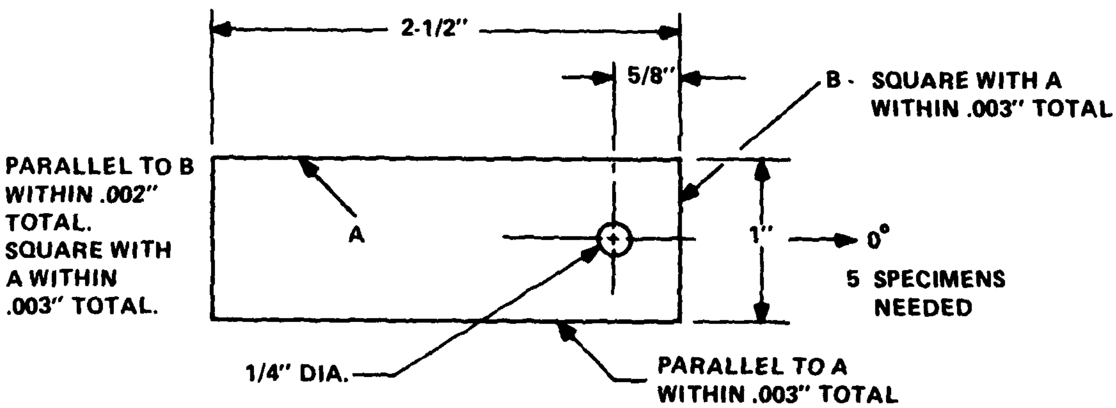

Figure 5. Bearing Specimen
(Compression Loading)

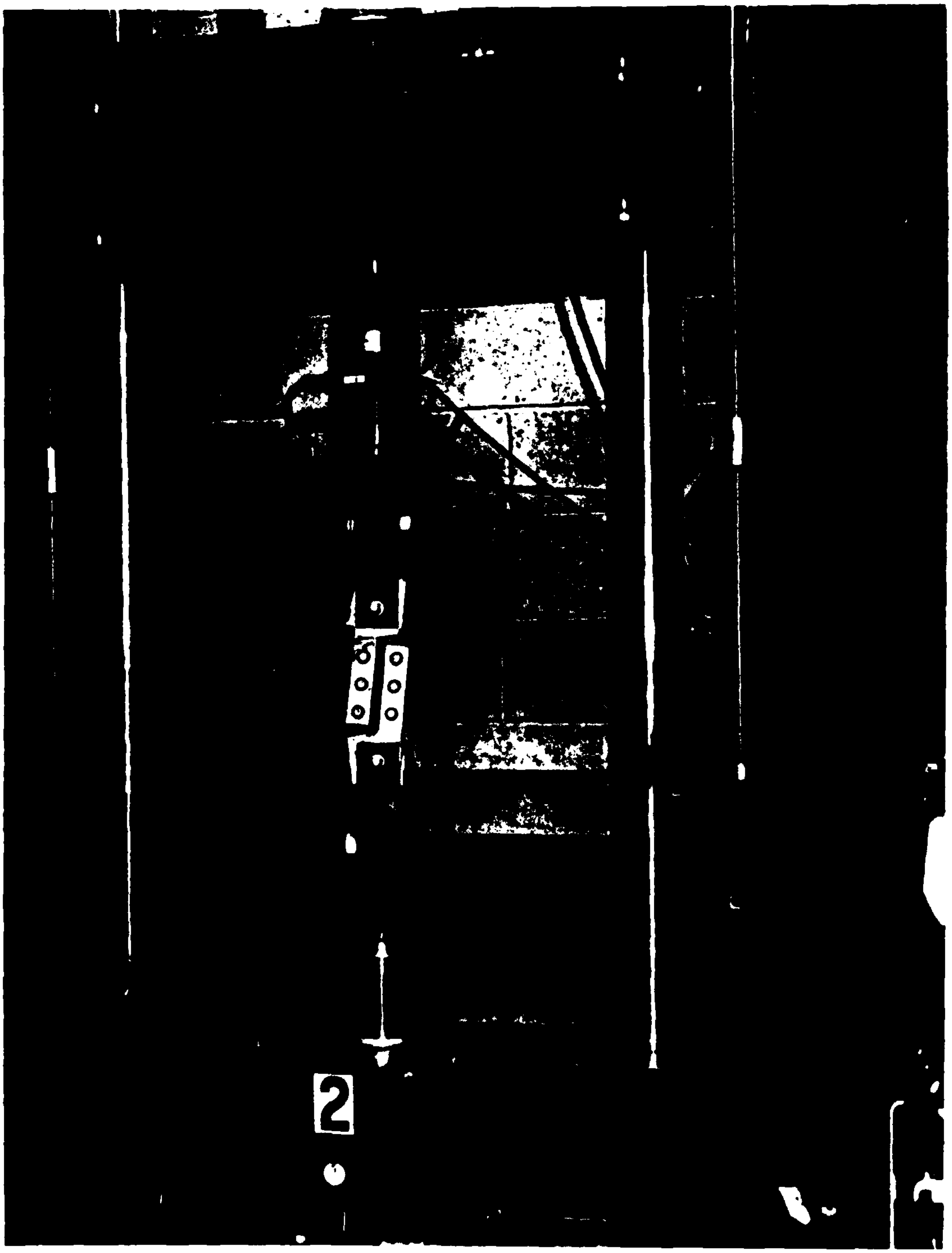

Figure 6. Rail Shear Test Set-Up

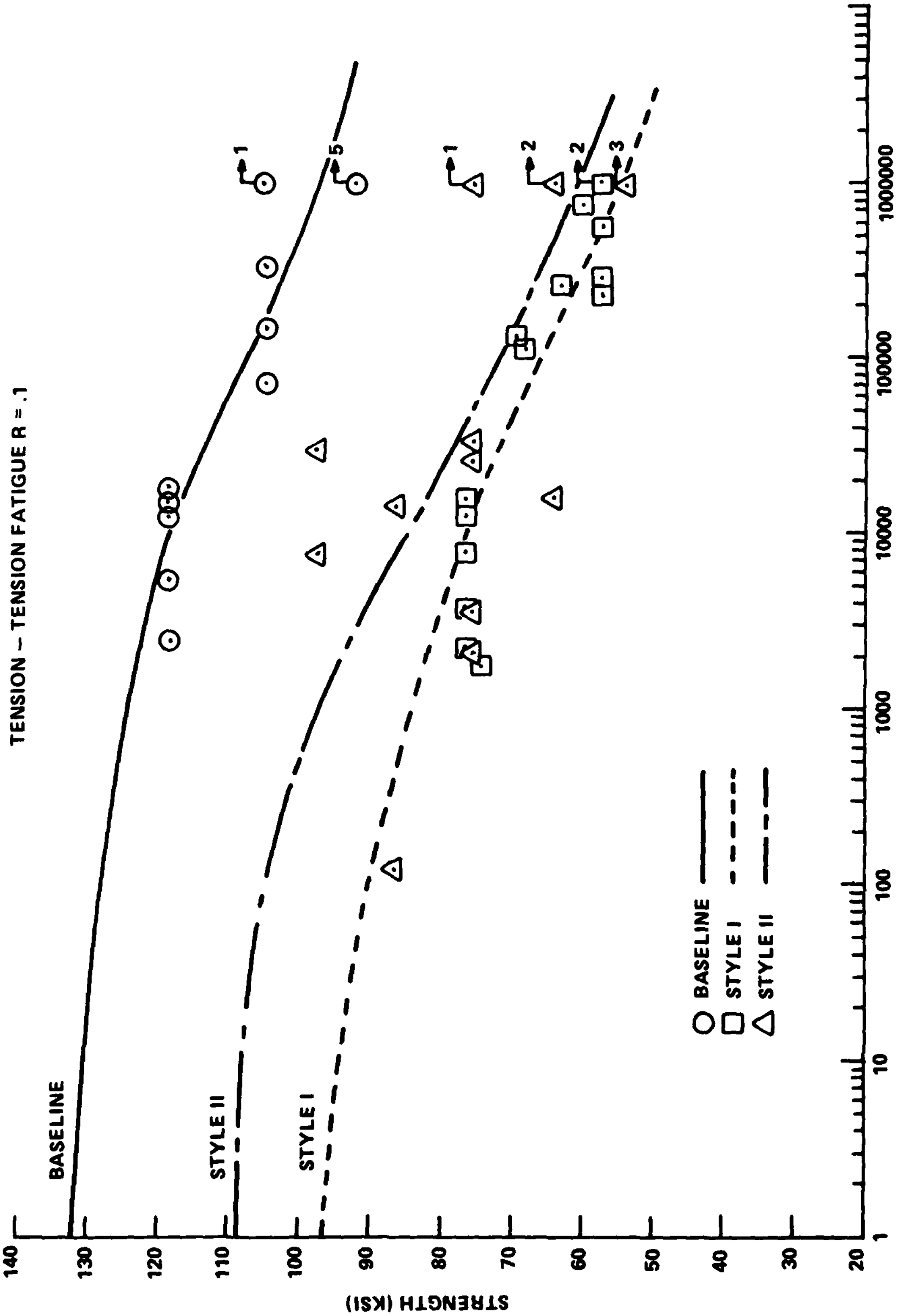

Figure 7. Life to Failure, R=0.1

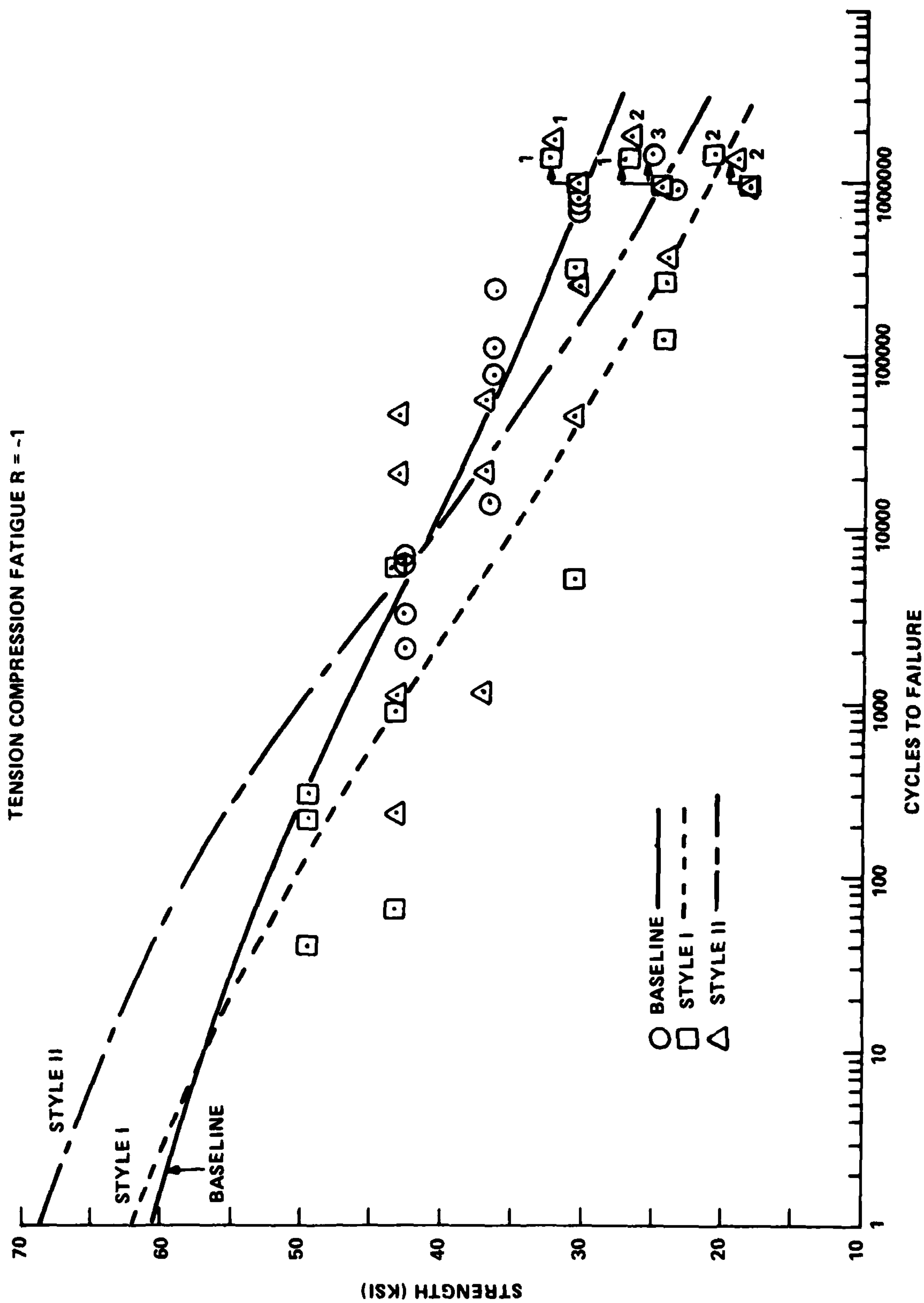

Figure 8. Life to Failure R=-1

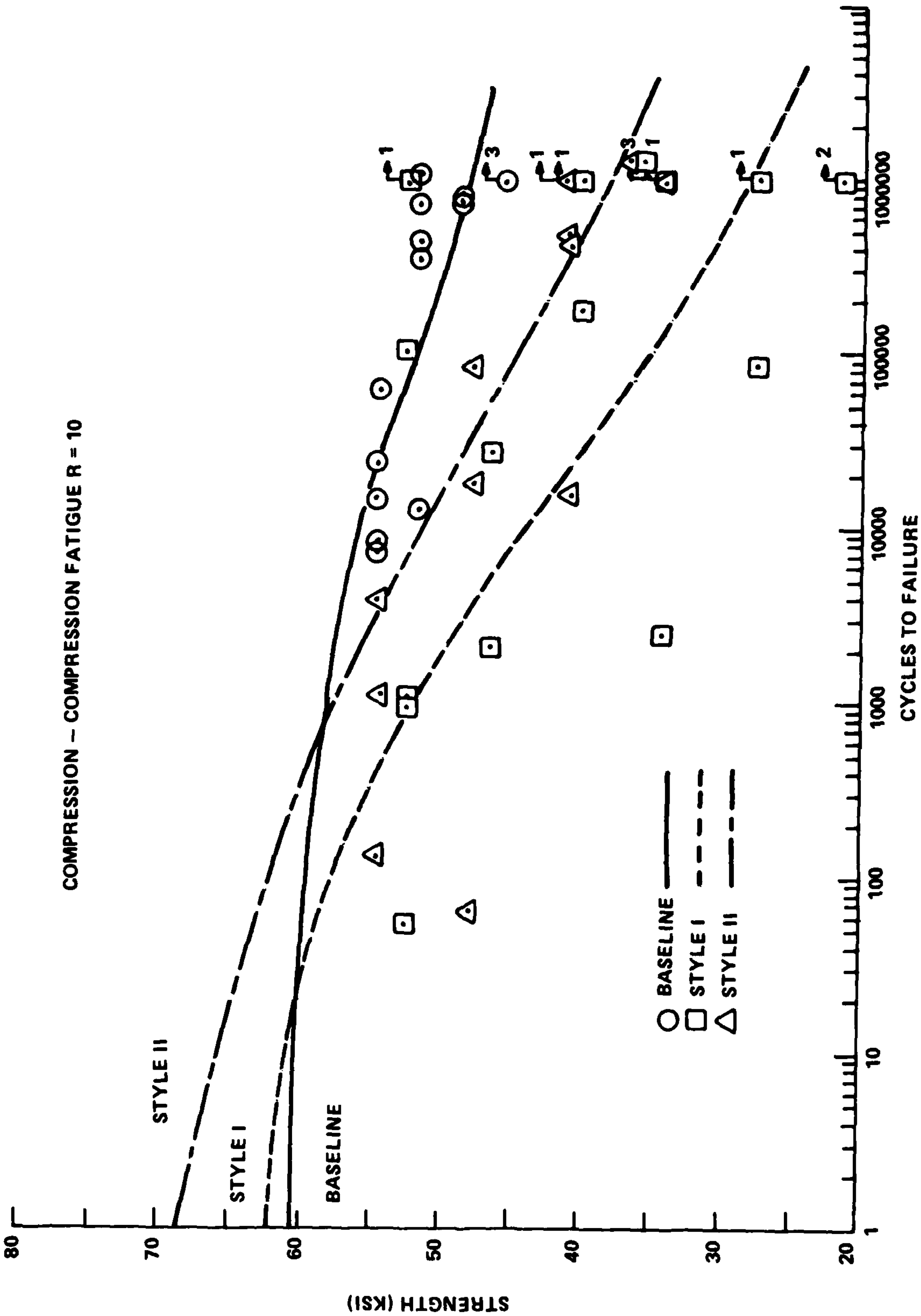

Figure 9. Life to Failure, R=10

Figure 10. Failed Fatigue Specimens R=.1

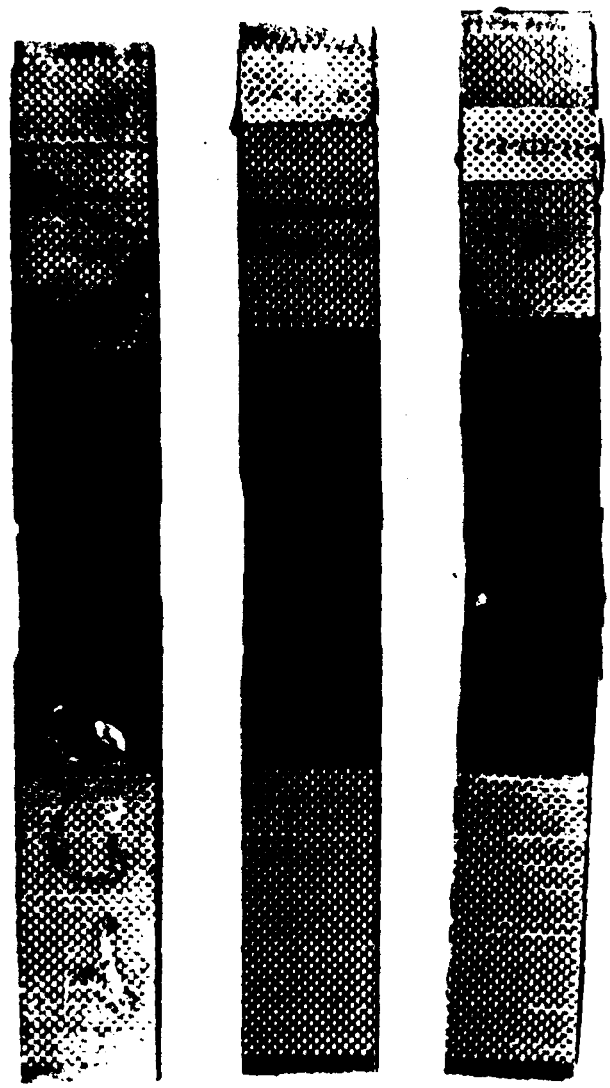

Figure 11. Failed Fatigue Specimens R=-1

Figure 12. Failed Fatigue Specimens R=10

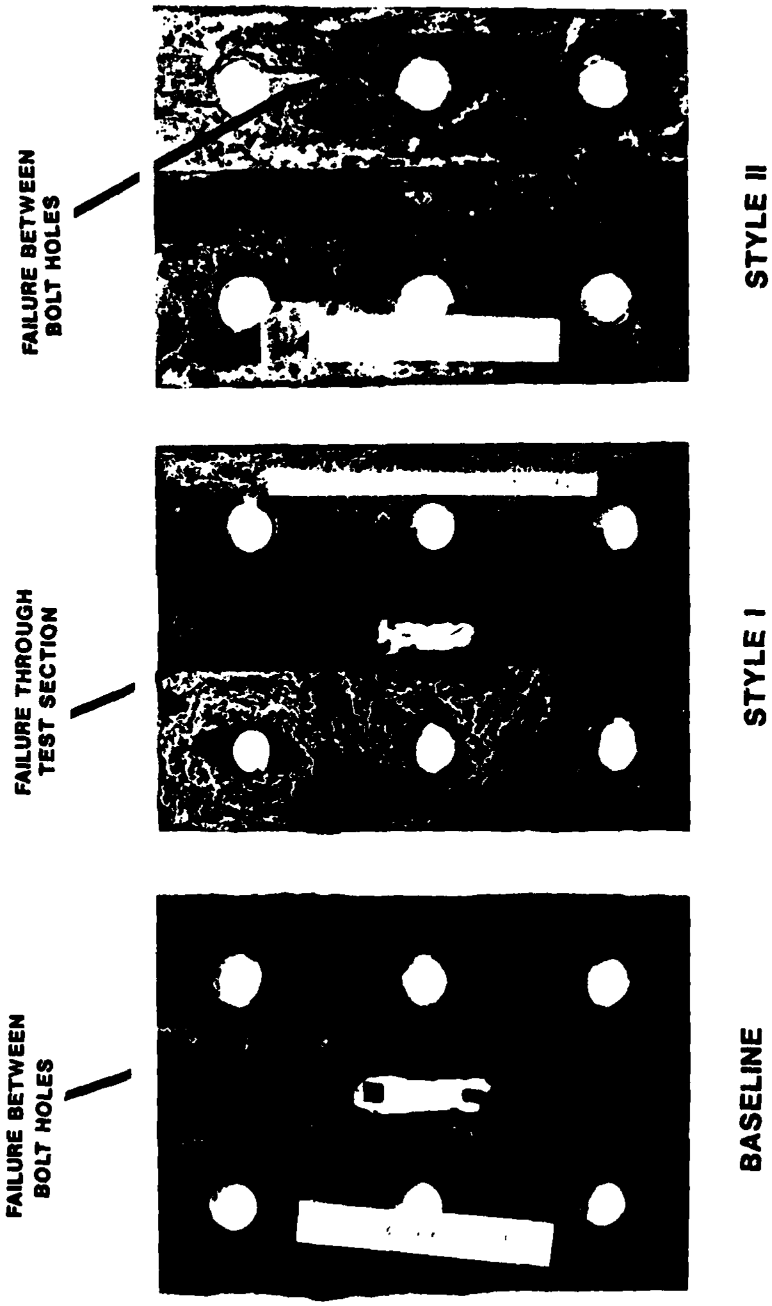

Figure 13. Failed Rail Shear Specimens

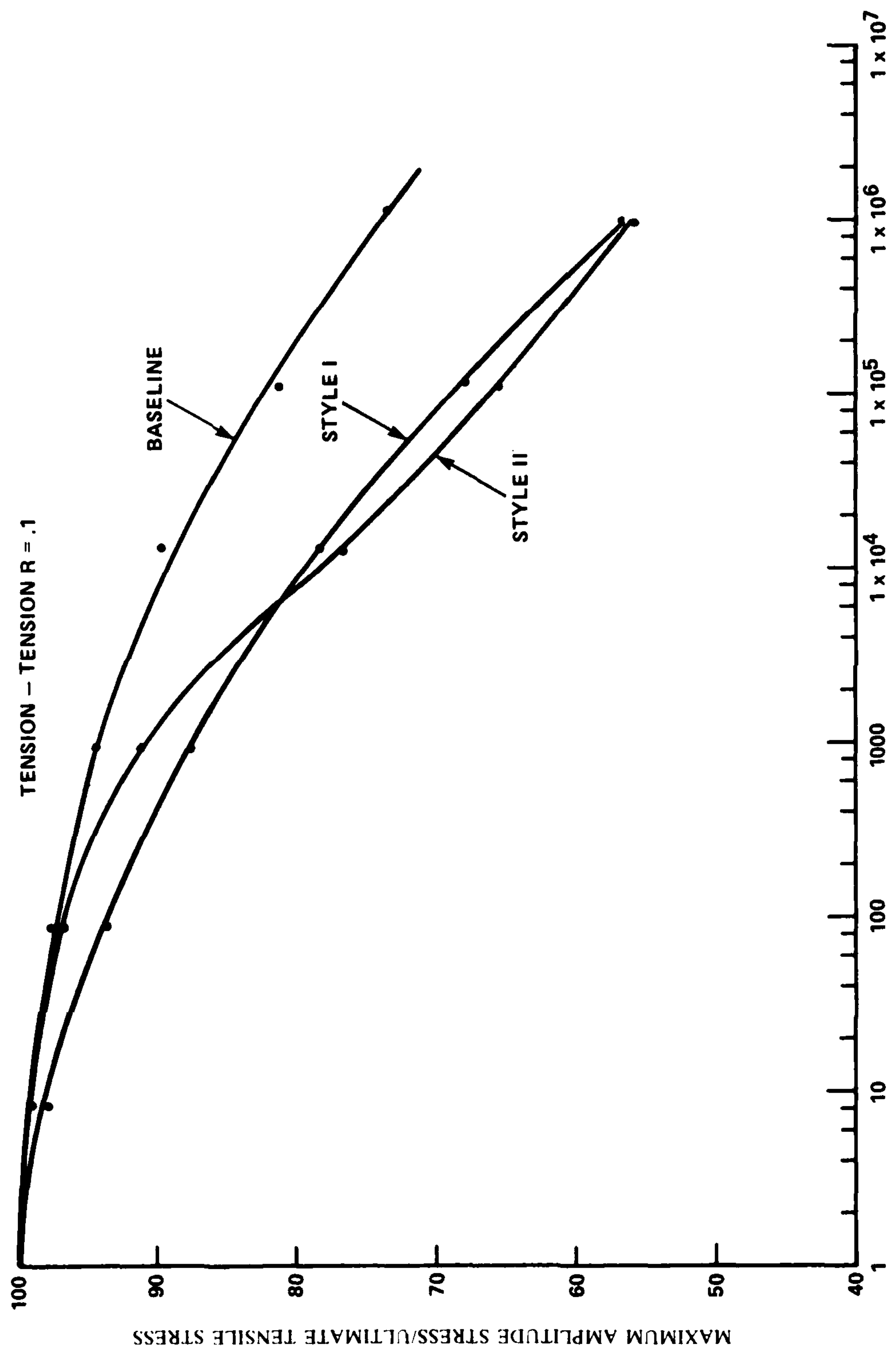

Figure 14. S-N Curve, R=.1 (S-Nondimensionalized)

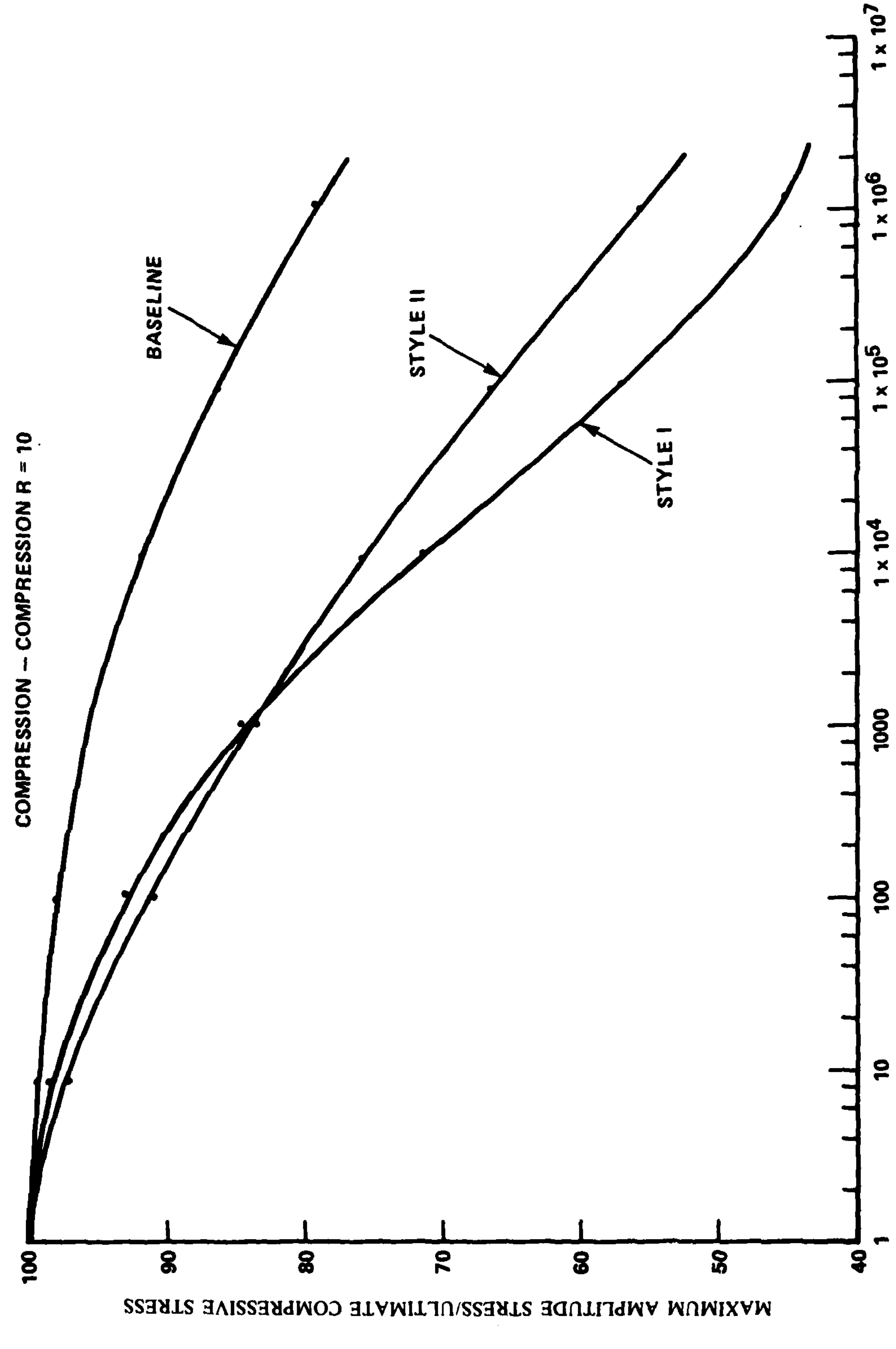

Figure 15. S-N Curve, R = 10 (S-Nondimensionalized)

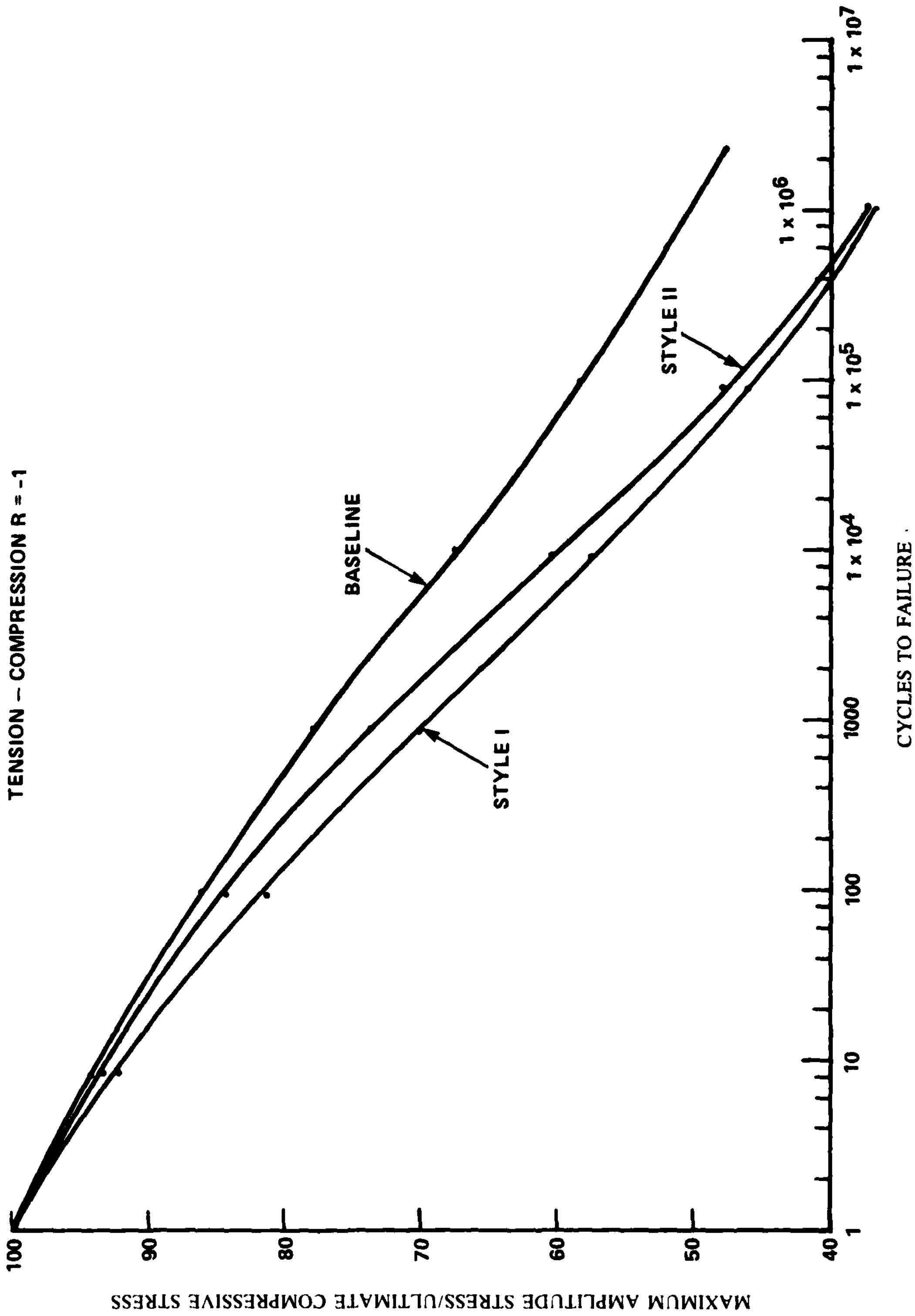

Figure 16. S-N Curve, R = 1 (S-Nondimensionalized)

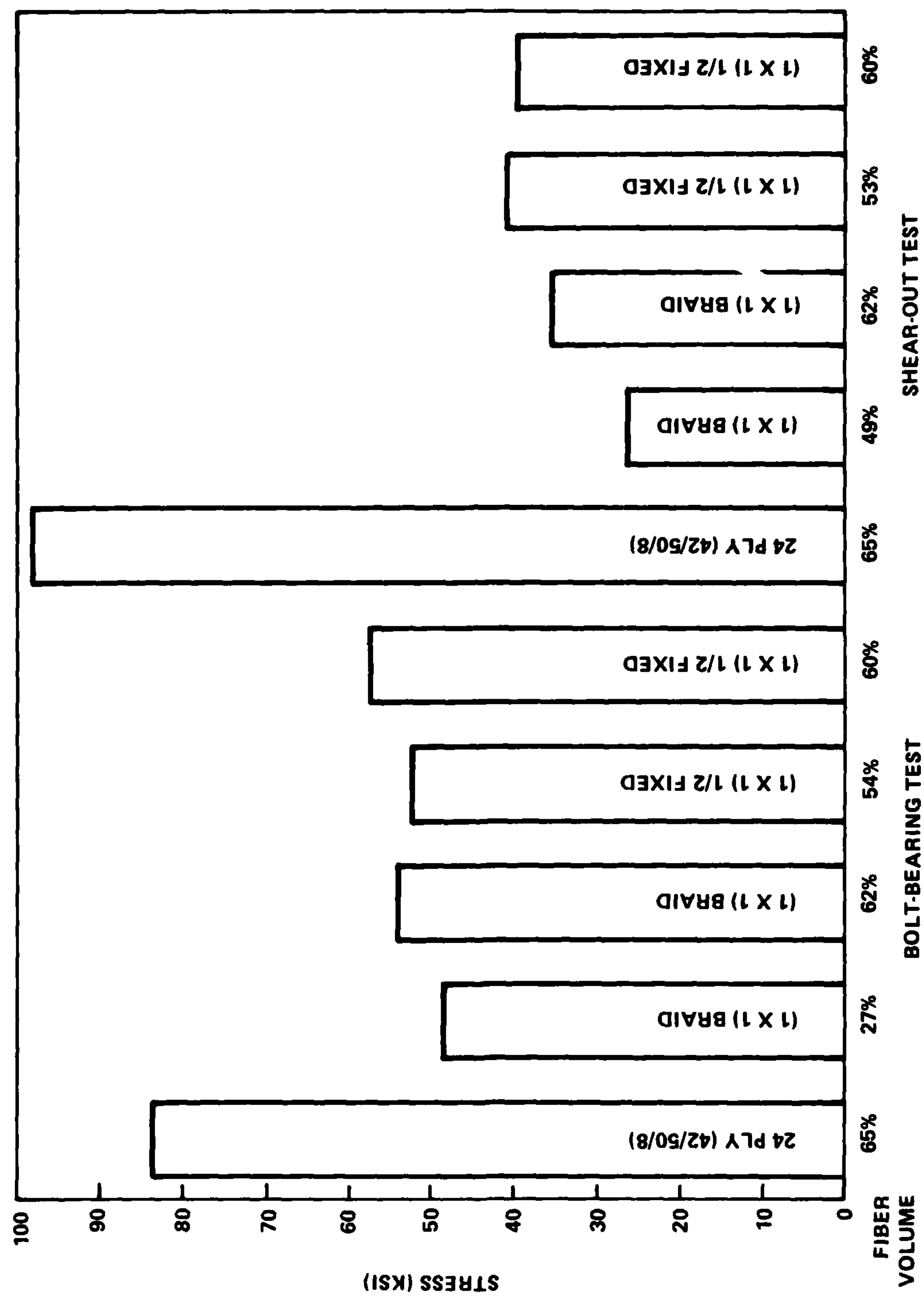

Figure 17. Bolt-Bearing and Shear-Out Test Results

APPENDIX A – FATIGUE TEST DATA

LABORATORY TEST SHEET

4ND-NADC-3960/45 (3-71)

LABORATORY: 6043

TEST OF: TENSION – TENSION FATIGUE OF BASELINE LAMINATE

TEST ENGINEER | OBSERVERS | DATE

TEST EQUIPMENT: R = .1 σ^{tu} = 132.0 KSI

SPECIMEN NUMBER	A IN²	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	PERCENT OF ULTIMATE STRENGTH KSI				
1B9	.1226	11.32	–	14240	116.15	70%	(92.4)				
1B1	.1264	11.68	–	17500	138.5	"	"				
1B4	.1222	11.29	–	15280	125.0	"	"				
1B13	.1216	11.24	–	14660	120.6	"	"				
1A8	.1231	11.37	–	16160	131.3	"	"				
1A10	.1218	12.86	–	15760	129.4	80%	(105.6)				
1A5	.1220	12.88	325751	–	–	"	"				
1A1	.1224	12.92	72236	–	–	"	"				
1B11	.1219	12.88	169031	–	–	"	"				
1A15	.1225	12.93	168411	–	–	"	"				
1B2	.1220	14.49	5419	–	–	90%	(118.8)				
1A4	.1236	14.68	2424	–	–	90%	(118.8)				
1A14	.1224	14.34	12512	–	–	"	"				
1B12	.1226	14.56	18734	–	–	"	"				
1B17	.1223	14.52	14722	–	–	"	"				

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY
6043

TEST OF
MAGNAWEAVE TENSION – TENSION FATIGUE OF STYLE I (ARC I)

TEST ENGINEER	OBSERVERS	DATE
ALPER	GAUSE	

TEST EQUIPMENT

$\sigma^{tu} = 96.8$ KSI

SPECIMEN NUMBER ARC I	A IN^2	$\theta°$	V_f %	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI		
XVII-E-6	0.1198	17	60	8.246	105027	–	–	71%	(68.8)		
XX-D-6	0.1295	13	62.5	8.246	267422	–	–	66%	(63.7)		
XX-B-6	0.1108	18	62.5	8.220	1864	–	–	76.6%	(74.2)		
XXII-E-6	0.1352	19	65	8.220	752476	–	–	63%	(60.8)		
XIX-D-6	0.1178	14	63	8.220	133441	–	–	72%	(69.8)		
XVII-D-6	0.1321	13	60	7.680	–	16520	125.1	60%	(58.0)		
XX-E-6	0.1298	16	62.5	7.530	583075	–	–	60%	(58.0)		
XIX-E-6	0.1143	14	63	6.630	–	11020	96.4	60%	(58.0)		
XVII-F-6	0.1150	19	60	6.670	229740	–	–	60%	(58.0)		
XX-C-6	0.1113	17	62.5	6.450	295717	–	–	60%	(58.0)		
XIX-C-6	0.1026	NG	63	7.900	7718	–	–	80%	(77.0)		
XX-F-6	0.1143	18	62.5	8.816	3708	–	–	80%	(77.2)		
XVIII-L-6	0.1143	NG	66	8.820	12553	–	–	80%	(77.2)		
XIX-B-6	0.1010	16	63	7.800	2173	–	–	80%	(77.2)		
XVII-K-6	0.1103	15	60	8.515	16373	–	–	80%	(77.2)		

NG – NOT GIVEN

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY
6043

TEST OF
MAGNAWEAVE TENSION – TENSION FATIGUE OF STYLE II (ARC II)

TEST ENGINEER
DALRYMPLE

OBSERVERS

DATE
10/83

TEST EQUIPMENT
22 KIPS MTS

σ^{tu} = 108.7 KSI

SPECIMEN NUMBER ARC II	A IN²	θ°	V_f %	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI		
XXII-I-6	0.1447	20.0	58.1	11.01	–	19120	132.1	70%	(76.09)		
XX-D-6	0.1574	23.5	56.15	11.98	2025	–	–	"	"		
XVII-C-6	0.1494	22.9	62.6	11.36	26784	–	–	"	"		
XVIII-A-6	0.1529	24.9	61.51	11.63	3502	–	–	"	"		
XVI-F-6	0.1569	22.5	62.8	11.94	32183	–	–	"	"		
IX-E-6	0.1477	25.8	62.9	8.028	–	15240	103.2	50%	(54.35)		
XVI-D-6	0.1485	16.5	62.8	8.071	–	18720	126.1	"	"		
XXII-E-6	0.1490	20.0	58.1	8.098	–	17980	120.7	"	"		
XVIII-B-6	0.1569	24.9	61.51	10.23	17263	–	–	60%	(65.22)		
XX-C-6	0.1482	19.3	56.15	9.666	–	16980	114.6	"	"		
XXII-D-6	0.1546	19.2	58.1	10.083	–	18360	118.8	"	"		
IX-A-6	0.1431	27.4	62.9	12.444	15735	–	–	80%	(86.96)		
XVI-E-6	0.1595	24.9	62.8	13.870	110	–	–	"	"		
XIV-C-6	0.1495	17.3	62.8	14.626	7255	–	–	90%	(97.83)		
XIII-B-6	0.1447	18.7	65.7	14.156	29716	–	–	"	"		

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY

TEST OF
TENSION COMPRESSION FATIGUE OF BASELINE LAMINATE

TEST ENGINEER
DALRYMPLE

OBSERVERS

DATE

TEST EQUIPMENT
σ^{cu} = 60.9 KSI

SPECIMEN NUMBER	A IN^2	P KIPS	CYCLE TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI			
2D8	0.125	5.329	3117	–	–	70%	(42.6)			
2E11	0.126	5.371	6657	–	–	70%	(42.6)			
2C6	0.123	5.243	2016	–	–	70%	(42.6)			
2D14	0.124	4.531	81780	–	–	60%	(36.5)			
2E12	0.125	4.568	14817	–	–	60%	(36.5)			
2C9	0.124	4.531	238497	–	–	60%	(36.5)			
2D6	0.125	3.806	706200	–	–	50%	(30.45)			
2D15	0.125	3.776	844673	–	–	50%	(30.45)			
2E15	0.125	3.806	773789	–	–	50%	(30.45)			
2D9	0.125	3.045	–	17640	141.1	40%	(24.36)			
2E4	0.126	3.069	–	15460	122.7	40%	(24.36)			
2C1	0.124	3.021	–	17300	139.5	40%	(24.36)			
2D12	0.125	3.806	952216	–	–	50%	(30.45			
2D3	0.125	4.568	107162	–	–	60%	(36.5)			
2E13	0.125	5.329	6616	–	–	70%	(42.6)			

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY: 6043

TEST OF: MAGNAWEAVE
TENSION – COMPRESSION FATIGUE OF STYLE I (ARC I)

TEST ENGINEER: DALRYMPLE | OBSERVERS: | DATE: 1/84

TEST EQUIPMENT: 22 KIP MTS $\sigma^{cu} = 62.1$ KSI

SPECIMEN NUMBER ARCI	A IN^2	θ°	V_f %	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI	
XIX-L-7	0.1331	NG	63	4.1328	–	14840	111.5	50%	(31.05)	
XXIV-C-7	0.1219	20	63	3.785	5161	–	–	50%	(31.05)	
XIX-J-7	0.0980	NG	63	3.0429	312491	–	–	50%	(31.05)	
XXIV-D-7	0.1276	NG	63	3.170	274539	–	–	40%	(24.84)	
XX-L-7	0.1165	17	62.5	2.170	–	13460	115.5	30%	(18.63)	
XXIV-A-7	0.1413	NG	63	2.632	–	15580	110.3	30%	(18.63)	FAILED IN TAB AREA
XXI-A-7	0.1383	NG	53	3.4354	131957	–	–	40%	(24.84)	DELAMINATED PRIOR TO 120,000 CYCLES
XX-J-7	0.1066	17	62.5	2.648	–	10340	96	40%	(24.84)	
XXI-B-7	0.1398	NG	53	6.077	66	–	–	70%	(43.47)	
XX-J-7	0.1173	17	62.5	5.099	6076	–	–	70%	(43.47)	
XX-I-7	0.1236	17	62.5	5.351	893	–	–	70%	(43.47)	
XIX-K-7	0.1043	NG	63	5.182	217	–	–	80%	(49.68)	
XXIV-B-7	0.1268	20	63	6.299	40	–	–	80%	(49.68)	
XIX-I-7	0.1069	NG	63	5.311	299	–	–	80%	(49.68)	

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY
6043

TEST OF MAGNAWEAVE
TENSION – COMPRESSION FATIGUE OF STYLE II (ARC II)

TEST ENGINEER
DALRYMPLE

OBSERVERS

DATE
2/84

TEST EQUIPMENT

$\sigma^{cu} = 68.6$ KSI

SPECIMEN NUMBER ARC II	A IN^2	θ°	V_f %	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	KSI	PERCENT OF ULTIMATE STRENGTH	KSI		
XV-A-7	0.1183	19.3	62.5	3.673	294071	–	–	45.3%	(31.05)		
X-J-7	0.1545	27.3	52.7	3.838	377278	–	–	36.2%	(24.84)		
IX-H-7	0.1400	22.5	62.9	2.608	–	14300	102.1	27.15%	(18.63)		
KI-B-7	0.1385	24.9	61.0	2.580	–	15000	108.3	27.15%	(18.63)		
XX-A-7	0.1517	16.8	56.15	3.768	–	17940	118.3	36.2%	(24.84)		
XV-F-7	0.1386	23.0	62.5	3.443	–	13220	95.4	36.2%	(24.84)		
XII-D-7	0.1558	22.5	61.0	4.838	–	18480	118.6	45.3%	(31.05)		
X-C-7	0.1639	24.1	52.7	5.089	47940	–	–	45.3%	(31.05)		
XVII-A-7	0.1444	20.5	62.6	5.380	1191	–	–	54.3%	(37.26)		
XI-G-7	0.1526	23.3	61.0	5.686	57354	–	–	54.3%	(37.26)		
X-D-7	0.1684	23.0	52.7	7.320	1152	–	–	63.4%	(43.47)		
XXII-B-7	0.1519	30.9	58.1	6.603	221	–	–	63.4%	(43.47)		
XIV-E-7	0.1688	18.0	55.6	7.338	48964	–	–	63.4%	(43.47)		
XXII-A-7	0.1466	23.5	58.1	5.462	20618	–	–	54.3	(37.26)		

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY

TEST OF MAGNAWEAVE
COMPRESSION – COMPRESSION FATIGUE OF BASELINE LAMINATE

TEST ENGINEER | OBSERVERS | DATE

TEST EQUIPMENT

$\sigma^{cu} \cong 60.9$ KSI

SPECIMEN NUMBER	A IN^2	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI
2E7	0.125	6.858	61923	–	–	90	(54.81)
2D7	0.124	6.796	16567	–	–	90	(54.81)
2C7	0.125	6.844	8409	–	–	90	(54.81)
2D5	0.126	6.927	23230	–	–	90	(54.81)
2C10	0.126	6.927	7316	–	–	90	(54.81)
2E1	0.129	6.676	362115	–	–	85	(51.8)
2E6	0.125	6.456	1048054	–	–	85	(51.8)
2C3	0.130	6.727	13847	–	–	85	(51.8)
2D4	0.131	6.806	762160	–	–	85	(51.8)
2D11	0.130	6.741	434511	–	–	85	(51.8)
2E2	0.126	6.142	718619	–	–	80	(48.7)
2E8	0.125	6.088	77138	–	–	80	(48.7)
2D13	0.124	6.051	–	5660	45.6	75	(45.68)
2C7	0.122	5.941	–	7680	62.9	75	(45.68)
2D2	0.122	5.930	–	8160	66.9	75	(45.68)

LABORATORY TEST SHEET
4ND-NADC-3960/45 (3-71)

LABORATORY
6043

TEST OF
MAGNAWEAVE COMPRESSION – COMPRESSION FATIGUE OF STYLE I (ARC I)

TEST ENGINEER
DALRYMPLE

OBSERVERS

DATE

TEST EQUIPMENT

σ^{cu} = 62.1 KSI

SPECIMEN NUMBER ARC I	A IN^2	$\theta°$	V_f %	P KIPS	CYCLE TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI		
XXI-C-8	0.1345	NG	53	6.266	29274	–	–	75%	(46.58)		
XXII-A-8	0.1384	22	65	6.444	2017	–	–	"	"		
XVIII-F-8	0.1022	NG	66	4.125	–	7300	71.4	65%	(40.37)		
XXI-E-8	0.1292	NG	53	5.217	181705	–	–	"	"		
XVIII-E-8	0.0975	NG	66	3.330	–	6700	68.7	55%	(34.15)		
XXI-M-8	0.1370	27	53	4.678	2583	–	–	"	"		
XVIII-C-8	0.1100	NG	66	3.074	–	8900	80.9	45%	(27.90)		
XXI-N-8	0.1369	27	53	3.825	89996	–	–	"	"		
XXIV-G-8	0.1184	14	63	2.573	–	9640	81.4	35%	(21.74)		
XXI-D-8	0.1266	NG	53	2.752	–	7740	61.1	"	"		
XXIV-F-8	0.1346	14	63	7.104	–	12200	90.6	85%	(52.78)		
XVIII-D-8	0.1076	NG	66	5.679	1037	–	–	"	"		
XXI-F-8	0.1339	14	53	7.066	991	–	–	"	"		
XXIV-H-8	0.1095	14	63	5.779	106552	–	–	"	"		
XXII-B-8	0.1220	22	65	6.441	53	– –	–	"	"		

NG – NOT GIVEN

LABORATORY TEST SHEET

4ND-NADC-3960/45 (3-71)

LABORATORY
6043

TEST OF
MAGNAWEAVE COMPRESSION – COMPRESSION FATIGUE OF STYLE II (ARC II)

TEST ENGINEER
DALRYMPLE

OBSERVERS

DATE
11/83

TEST EQUIPMENT
22 KIP MTS

σ^{cu} = 68.58 KSI

SPECIMEN NUMBER ARC II	A IN^2	$\theta°$	V_f %	P KIPS	CYCLES TO FAILURE	RESIDUAL STRENGTH LBS	RESIDUAL STRENGTH KSI	PERCENT OF ULTIMATE STRENGTH	KSI		
X-K-8	0.1501	27.4	52.7	5.147	–	8200	54.63	50%	(34.29)		
XV-B-8	0.1236	21.8	62.5	4.238	–	8700	70.39	50%	(34.29)		
XX-F-8	0.1572	22.0	56.15	5.390	–	13000	82.70	50%	(34.29)		
XII-E-8	0.1472	28.2	61.0	8.076	137	–	–	80%	(54.86)		
X-F-8	0.1620	25.3	52.7	7.777	18201	–	–	70%	(48.01)		
XVII-B-8	0.1470	22.3	62.6	6.049	–	9520	64.76	60%	(41.15)		
XIV-A-8	0.1470	26.3	55.6	6.049	488977	–	–	60%	(41.15)		
XX-B-8	0.1452	24.3	56.15	7.966	3924	–	–	80%	(54.86)		
X-I-8	0.1586	27.5	52.7	8.701	1101	–	–	80%	(54.86)		
XXII-C-8	0.1560	23.0	58.1	6.419	421972	–	–	60%	(41.15)		
XVII-E-8	0.1436	24.3	62.6	6.894	85340	–	–	70%	(48.01)		
XIV-B-8	0.1451	28.0	55.6	6.966	64	–	–	70%	(48.01)		
XV-E-8	0.1289	26.6	62.5	6.188	15683	–	–	60%	(41.15)		

APPENDIX B – STATIC TEST DATA

RAIL SHEAR TEST RESULTS

SPECIMEN #	STYLE TYPE	VOLUME FRACTION, %	BRAID ANGLE, θ	AVERAGE THICKNESS, t (IN.)	SHEAR MODULUS G_{12} (MSI)*
1	BASELINE	65	–	.127	4.17
2 +	BASELINE	65	–	–	–
3	BASELINE	65	–	.127	2.60
4	BASELINE	65	–	.124	2.34
5 ++	BASELINE	65	–	–	–
XIII D4	I	30	22.0	.161	1.59
XIII A4	I	30	27.0	.164	1.40
III A4	I	51	–	.141	1.48
X C4	I	33	25.0	.172	3.83
XIII C4	I	30	23.0	.161	1.01
IV A4	II	58.1	28.2	.106	2.25
VIII B4	II	55.0	37.3	.128	2.22
XXI B4	II	54.2	23.4	.151	1.41
XXI D4	II	54.2	21.9	.143	1.34
IV B4 +	II	58.1	30.2	.119	–

*BASED ON STRAIN READINGS BETWEEN LOADS OF 100 LBS. AND 500 LBS.
+SPECIMEN WAS DAMAGED PRIOR TO TESTING
++INVALID TEST RESULTS

BEARING COMPRESSION TEST

SPECIMEN				LOAD (LB)	AREA (t·d) IN^2	STRESS (KSI)	
TYPE	θ	NUMBER	V_f				
I	16°	17-J-9	60%	1460	.0283	51.64	
I	16°	20-H-9	63%	1640	.0317	51.78	
I	18°	20-G-9	63%	1300	.0288	45.22	$\sigma^c_{br_{Ave}}$ = 54.12 KSI
I	16°	17-I-9	60%	1860	.0304	61.23	
I	13°	19-F-9	63%	1520	.0250	60.74	C.V. = 12.6%
II	21.1°	13-A-9	66%	2300	.0349	65.90	
II	29.2°	9-C-9	63%	1820	.0349	52.11	
II	25.4°	18-C-9	62%	2080	.0398	52.23	$\sigma^c_{br_{Ave}}$ = 57.53
II	23.3°	22-G-9	58%	2360	.0393	60.13	
II	22.6°	14-D-9	56%	2180	.0381	57.29	C.V. = 10.1%

BEARING TENSION TEST

SPECIMEN				LOAD	(t·d) AREA	$\frac{P}{t \cdot d}$ STRESS	
TYPE	θ	NUMBER	V_f	(LB)	(IN²)	(KSI)	
I	13°	19-F-9	63%	820	0.0250	32.77	
I	18°	20-G-9	63%	960	0.0288	33.39	
I	16°	17-J-9	60%	1120	0.0283	39.61	$\sigma^t_{br\ ave}$ = 35.46 KSI
I	16°	20-H-9	63%	1160	0.0317	36.62	C.V. = 7.8%
I	16°	17-I-9	60%	1060	0.0304	34.90	
II	22.6°	14-D-9	56%	1180	0.0381	31.01	
II	29.2°	9-C-9	63%	2020	0.0349	57.84	$\sigma_{br\ ave}$ = 39.78 KSI
II	25.4°	18-C-9	62%	1540	0.0398	38.67	C.V. = 31.5%
II	23.3°	22-G-9	58%	1240	0.0393	31.59	

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