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FATIGUE BEHAVIOR OF HERCULES 3501-6 EPOXY RESIN

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Plates and solid rods of Hercules 3501-6 neat epoxy resin were cast, from which tensile, compressive and torsional shear specimens were machined. Half of the tensile specimens were moisture-preconditioned for six months at 65°C in a 98% RH environment. Room temperature static and fatigue tests were conducted, and a scanning electron microscope used to examine representative failure surfaces. Stress versus number of cycles to failure plots were prepared.

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Results indicate that the tensile fatigue strength is reduced by approximately 20 percent by moisture-preconditioning. Cycling rate appeared to also be very important, higher rates leading to shorter fatigue lives. The failure analysis indicated shear to be a failure mode present for all three loading conditions.

PREFACE

This Final Report summarizes a one-year research program, initiated in September 1978, sponsored by the Naval Air Development Center. The NADC Program Monitor was Mr. Lee W. Gause.

All work during this research program was performed by the Composite Materials Research Group within the Mechanical Engineering Department at the University of Wyoming. Co-Principal Investigators were Mr. David E. Walrath, Staff Scientist, and Dr. Donald F. Adams, Professor. Students making significant contributions to this work were Mr. Steven Hayes, Mr. Kevin Kiger, and Mr. Doug Cairns.

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SECTION 1

INTRODUCTION AND SUMMARY

1.1 Introduction

Research into the mechanical behavior of epoxy resins, Hercules 3501-6 resin in particular, has been underway by the Composite Materials Research Group at the University of Wyoming for over four years. This research was initiated in response to a need to determine the engineering constants of the resin for use in a micromechanics analysis of composite materials being developed at that time by the Composite Materials Research Group [1]. Static tension and torsion tests were conducted on Hercules 3501-6 neat epoxy specimens at ambient and elevated temperatures, for both dry and moisture-preconditioned specimens. Results from both the analytical and experimental work can be found in References [2-6], among others. It was found during this work that the Hercules 3501-6 resin, a hot-melt system, is extremely difficult to cast in the neat (unreinforced) form. Difficulties in the casting process were overcome, however, and a method was found to mold this material. This method is described in Appendix A.

Research into the fatigue behavior of advanced composites has been and still is being actively conducted. Some of the more significant recent efforts include those of References [6-10], among others. A detailed literature survey is given in Reference [6]. However, at the time the present investigation was initiated, and to the present time, relatively little has been done to characterize the fatigue behavior of the neat resin itself. The objective of the present work, therefore, was to characterize the fatigue behavior of Hercules 3501-6 neat epoxy resin by determining the strength versus number of cycles (S-N) curves of the material under tension-tension, compression-compression, and non-reversing torsion loadings. Effects of moisture-preconditioning and variations in cycling rate were also studied.

A series of tests were run to generate static and fatigue data. Strength versus number of cycles (S-N) curves were generated for tension-tension and compression-compression loadings. Unfortunately, equipment limitations did not permit the performance of torsion fatigue tests; however, static tests were performed. A number of tension and torsion specimens were preconditioned for 6 months in a 65°C., 98% R.H. environment, then used to measure static tension and torsion shear strengths, and to establish a tensile fatigue S-N curve.

Unless otherwise noted, all fatigue testing was performed at 5 cycles/sec. (5 Hz). A small number of dry tensile specimens were cycled at faster rates, i.e., 15 and 30 Hz, to examine the effect of cyclic rate on S-N behavior. Residual strength tests were also performed for the tension and compression loading modes. Failed specimens from the static tests were examined in a Scanning Electron Microscope (SEM) in an effort to identify failure modes.

1.2 Summary

To summarize the results of this program, it was found that the average static strengths for tension, compression, and torsional shear loadings were 58.5 MPa (8.49 ksi), 164 MPa (23.8 ksi), and 105 MPa (15.2 ksi), respectively. Cyclic tension and cyclic compression loading caused a linear reduction in strength with respect to the number of cycles when plotted on a semi-logarithmic scale. Moisture preconditioning produced a strength reduction on the order of 20 percent in both static tension and torsional shear strength. The slope of the tension-tension S-N curve was not altered significantly, however, suggesting that static tests may be sufficient to estimate the effects of absorbed moisture on fatigue behavior.

Cyclic tensile loading did tend to reduce residual tensile strength, but cyclic compressive loading tended to slightly increase residual compressive strength. Only a few tensile fatigue tests were conducted at increased cyclic rates and only on dry specimens; however, these did show that increased cyclic rate produced a reduction in fatigue life.

SEM examination of failed static test specimens showed evidence of a common failure mode for all three types of loading, viz, tension, compression, and torsional shear. The same rippled surface regions were evident in all three types of specimens. Two distinct types of failure regions were evident on the tensile specimen failure surfaces. One was similar to that seen in torsion and compression specimens, thought possibly to be due to shear. The other type of failure region could be due to tensile failure. Details of sample preparation and testing procedures as well as a more complete discussion of test results and failure surface examinations are included in the following sections and appendices.

SECTION 2

SPECIMEN CONFIGURATIONS AND TEST METHODS

2.1 Specimen Configurations

Casting the Hercules 3501-6 epoxy into neat resin specimens of consistent quality has been a difficult barrier to measuring the engineering properties of this material system. This hot-melt resin is subject to large amounts of outgassing during processing, making the casting of void-free shapes difficult. The method developed at the University of Wyoming and used to prepare specimens for this program is described in Appendix A.

The resin was cast into two shapes, either flat plates measuring 203 mm x 152 mm x 1.3 mm (8 in x 6 in x 0.05 in), or solid circular rods 153 mm (6 in) long with diameters of either 12.7 mm (0.5 in) or 6.3 mm (0.25 in). Tensile specimens were then cut and machined from the flat plates to a standard (ASTM D638) dogbone-shaped specimen, an example of which is shown in Figure 1. Compression specimens 25 mm (1 in) long were cut from the 12.7 mm diameter rods, the ends being ground smooth and parallel. Examples of compression specimens are shown in Figure 2. Torsion specimens were cut to a 100 mm (4 in) length from the 6.3 mm diameter rods, as shown in Figure 3.

2.2 Test Methods

Static testing was performed in an Instron Model 1125 electomechanical testing machine at rates of 2 mm/min for the tension and compression loadings, and 1 rad/min for the torsion loadings. Tensile strains were measured with an extensometer to calculate the elastic (Young's) modulus.

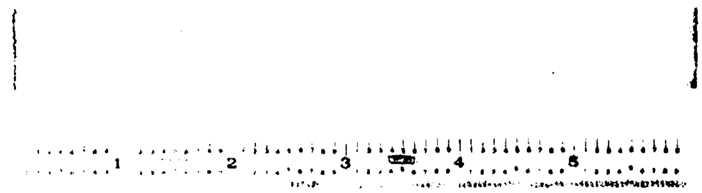

FIGURE 1

Hercules 3501-6 Neat Epoxy Resin Tensile Specimen

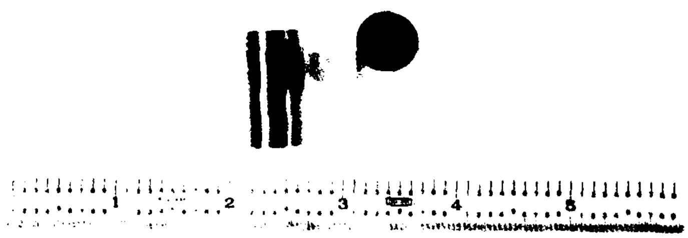

FIGURE 2

Hercules 3501-6 Neat Epoxy Compression Specimens

FIGURE 3

Hercules 3501-6 Neat Epoxy Torsional Shear Specimen

Angle of twist was measured during the torsion tests with the rotational equivalent of an extensometer, in order to calculate shear modulus. This "rotometer," designed and built at the University of Wyoming, uses a rotary variable differential transformer (RVDT), attached at two stations a prescribed distance apart on the specimen to define the gage length, in order to measure relative rotation and thus the shear strain. Compression strains were not measured due to the short gage length of the specimen; therefore no compression modulus values were obtained.

Fatigue testing was performed in an Instron Model 1321 servohydraulic testing machine using a stress ratio of R=0.1 and a cyclic rate of 5 Hz. A set of 4 dry tensile specimens were also tested at 15 and 30 Hz.

A linear regression technique was used to find an equation of the form S = A log N + B to describe the fatigue behavior for each loading mode, where S is peak stress, N is number of cycles, and A and B are constants, to be determined from the data. These equations were then used to establish the conditions for the residual strength tests, i.e., in predicting the peak stress at which specimens had to be cycled in order to expect failure at 10^2, 10^4, or 10^6 cycles. Specimens were cycled at 80 percent of these predicted stresses for the required number of cycles, then statically loaded to failure.

SECTION 3

EXPERIMENTAL RESULTS

3.1 Tensile Fatigue Results

3.1.1 Dry Specimens

Static, fatigue, and residual strength test results for room temperature tensile loading of the dry specimens are shown in Figure 4. The average static tensile strength of 58 MPa (8.5 ksi) is indicated by the dark circle on the left axis. The range of the data is indicated by the scatter bar. An average elastic modulus of 4.5 GPa (0.65 Msi) was measured for these static tests. Open circles indicate the peak cyclic stress and fatigue life of the 5 Hz fatigue tests. The regression equation which best fits these static and fatigue data points is of the form:

$$S = -4.94 \log N + 60.9 \text{ MPa}$$

and seems to represent the data fairly well. Using this equation, the life of the Hercules 3501-6 resin in tension fatigue will vary between one cycle at a stress of 61 MPa (8.8 ksi) to 10^6 cycles at a peak stress of 31 MPa (4.5 ksi), a fatigue strength reduction of 50% over a one million cycle life.

This equation was then used to estimate the values to be used for the residual strength tests, results of which are indicated by triangles in Figure 1. Tests performed for 10^2 cycles were cycled at a peak stress of 43 MPa (6.2 ksi), then statically loaded to failure. The solid triangle at 10^2 cycles indicates an average residual strength of 60 MPa (8.7 ksi) from 4 tests. Three tests were averaged to obtain the 44 MPa

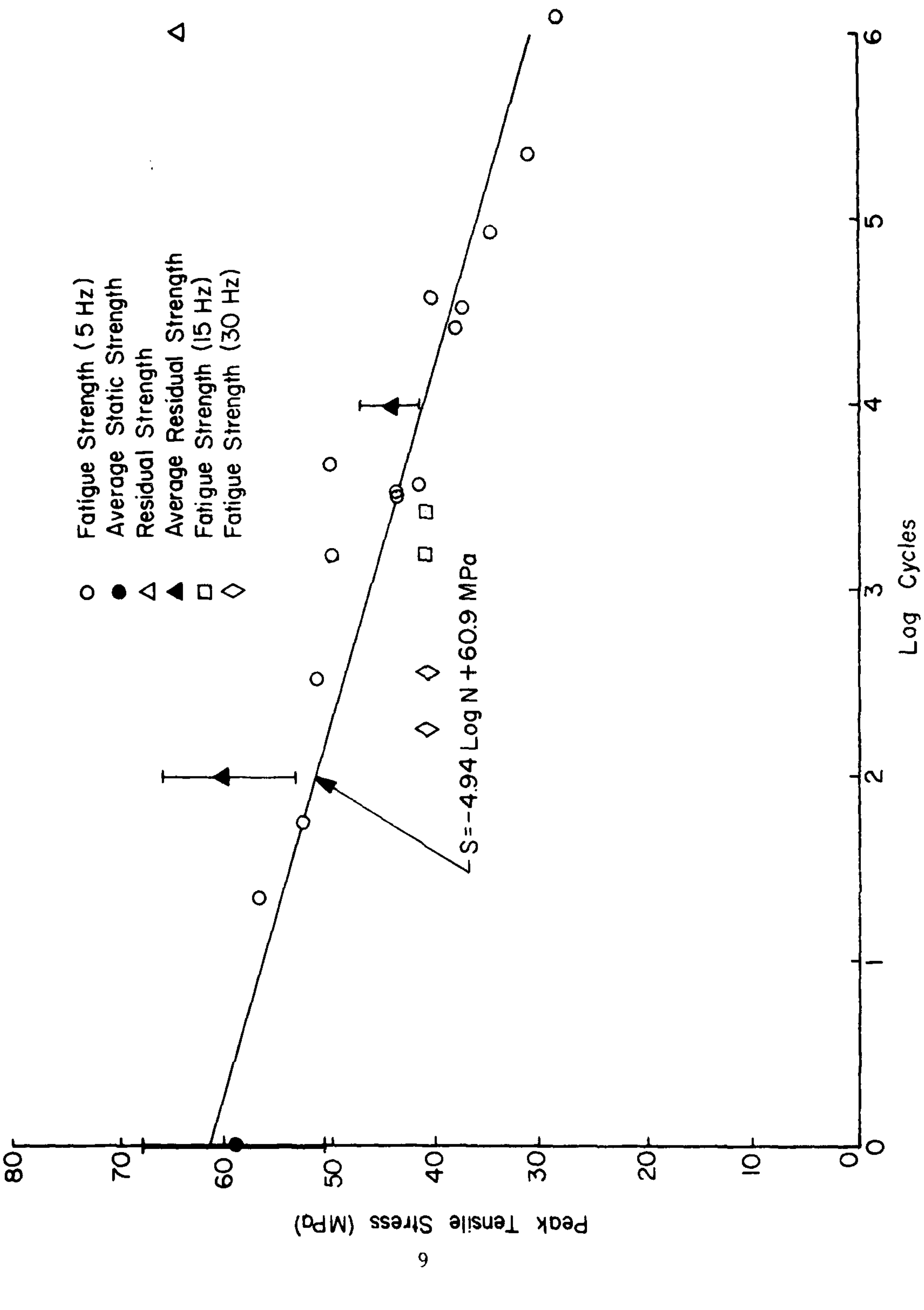

FIGURE 4

Tensile Static, Fatigue and Residual Strengths of Hercules 3501-6 Neat Epoxy Resin at Room Temperature (No Moisture Preconditioning)

(6.4 ksi) residual strength indicated at 10^4 cycles. These specimens were all cycled at a peak stress of 33 MPa (4.8 ksi). Only one residual strength test was performed at 10^6 cycles, as indicated by the open triangle. This specimen was cycled at a peak stress of 23 MPa (3.4 ksi), and failed at a static stress of 64 MPa (9.3 ksi). From the first two residual strength points it would seem that tensile cycling did produce some sort of progressive damage in the specimens as the residual strength tends to decrease with increasing cycling. However, the high residual strength value at 10^6 cycles contradicts this trend, although it is but one isolated data point.

Four higher cyclic rate fatigue tests were performed at a peak stress of 41 MPa (5.9 ksi), the stress level estimated to cause failure at 10^4 cycles. Two specimens, indicated by squares, were cycled at a rate of 15 Hz; two specimens, indicated by diamonds, were cycled at 30 Hz. As can be seen by these four tests, an increase in cyclic rate appears to produce a definite reduction in fatigue life. The two specimens cycled at 15 Hz failed after 1550 and 2050 cycles, instead of the predicted 10^4 cycles. The two specimens tested at 30 Hz failed after only 190 and 370 cycles.

3.1.2 Moisture Effects

A series of tensile static, fatigue, and residual strength tests were also performed on specimens which had been preconditioned for 6 months in a 65°C, 98% R.H. environment. Results of these tests are shown in Figure 5. As can be seen in Figure 5, the average static tensile strength of these moisture-preconditioned specimens was 45 MPa (6.6 ksi), as indicated by the solid circle; the average measured elastic modulus was

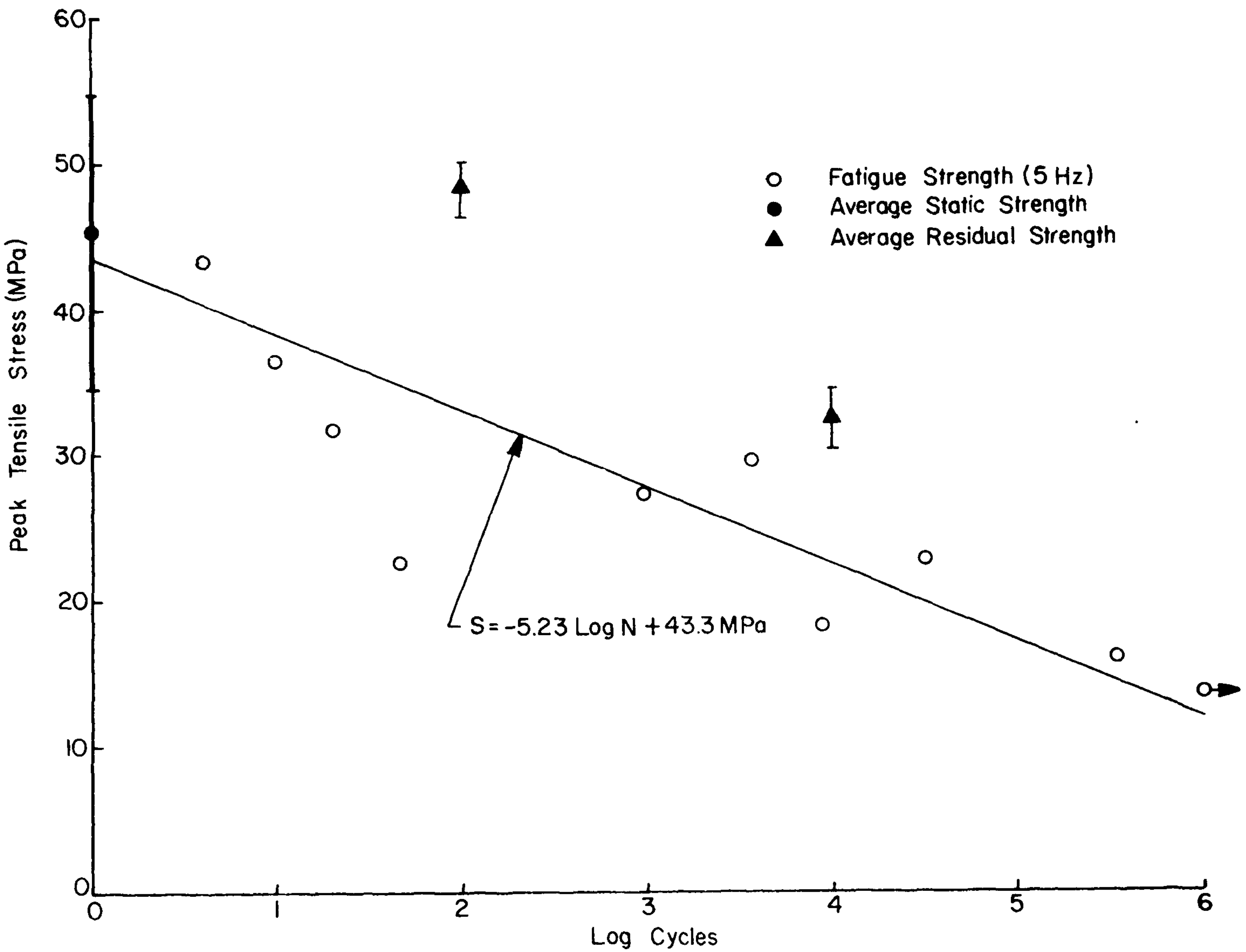

FIGURE 5

Tensile Static, Fatigue, and Residual Strengths of Hercules 3501-6 Neat Epoxy Resin at Room Temperature (Moisture-Preconditioned Specimens)

4.4 GPa (0.64 Msi). Although the fatigue points are somewhat more scattered than those from the dry specimens, the same data trend is apparent. The regression equation for these static and fatigue tests is:

$$S = -5.23 \log N + 43.3 \quad \text{MPa}$$

Comparing this equation to that from the dry tensile fatigue tests, it can be seen that the decrease in strength with increasing life, as represented by the slope constants, are approximately equal, i.e., -4.94 MPa dry as compared to -5.23 MPa wet. The moisture caused an approximately 30 percent drop in the static strength, as indicated by the second constants of the equations, i.e., 60.9 MPa dry as compared to 43.3 MPa wet. The actual decrease in static strength is about 22 percent when using the measured averages of 58 MPa (8.5 ksi) and 45 MPa (6.6 ksi) for the dry and preconditioned specimens, respectively. Comparing Figure 5 to Figure 4, it can be seen that absorbed moisture merely tended to shift the stress versus fatigue life down without radically changing the slope of the line. This would suggest, at least for tension-tension fatigue, that the effects of moisture absorption on fatigue strength could possibly be estimated using static tests with perhaps a few low cycle fatigue tests.

Residual strength tests were performed for lives of 10^2 and 10^4 cycles only; average residual strengths are shown as solid triangles. The average strengths of 48 MPa (7.0 ksi) and 32 MPa (4.7 ksi) for 10^2 and 10^4 cycle lives, respectively, indicate the same downward trend as the residual strength results from the dry specimen tests.

3.2 Compressive Fatigue Results

Results for the room temperature, dry compressive static, fatigue, and residual strength tests are plotted in Figure 6. No moisture-preconditioned compressive tests were run. The average static compressive strength of the Hercules 3501-6 specimens was 164 (23.8 ksi), as indicated by the solid circle. The fatigue data points, shown as open circles, ended up being grouped around 10^3 and 10^6 cycles. It was extremely difficult to estimate peak cycling stress values during testing to produce failures at chosen lifetimes. A small decrease in peak stress produced a test which ran out to 10^6 cycles or beyond. Slight increases in peak stress merely caused specimens to again fail in the 10^2 to 10^4 cycle region. Therefore, the data points tended to be grouped in two distinct regions. End loading effects probably played an important role in determining the life of any given compressive fatigue test. In retrospect, a straight-sided compression specimen was probably not the optimum choice. In future work, a specimen with a reduced cross section in the gage length will be tried. The regression equation for the static and fatigue data points was determined as:

$$S = -8.17 \log N + 165.4 \text{ MPa}$$

Comparing these results with the tensile fatigue results, it can be seen that the static compressive strength is much higher than the static tensile strength, and the compressive fatigue strength decreases at a more rapid rate with increasing life than does the tensile fatigue strength.

Compressive residual strength tests, results of which are shown as triangles in Figure 6, provided some interesting data. The compressive residual strengths did not decrease with increased cyclic loading as did the tensile residual strengths. In fact, the compressive residual strengths are higher than the average compressive static strength. This effect is

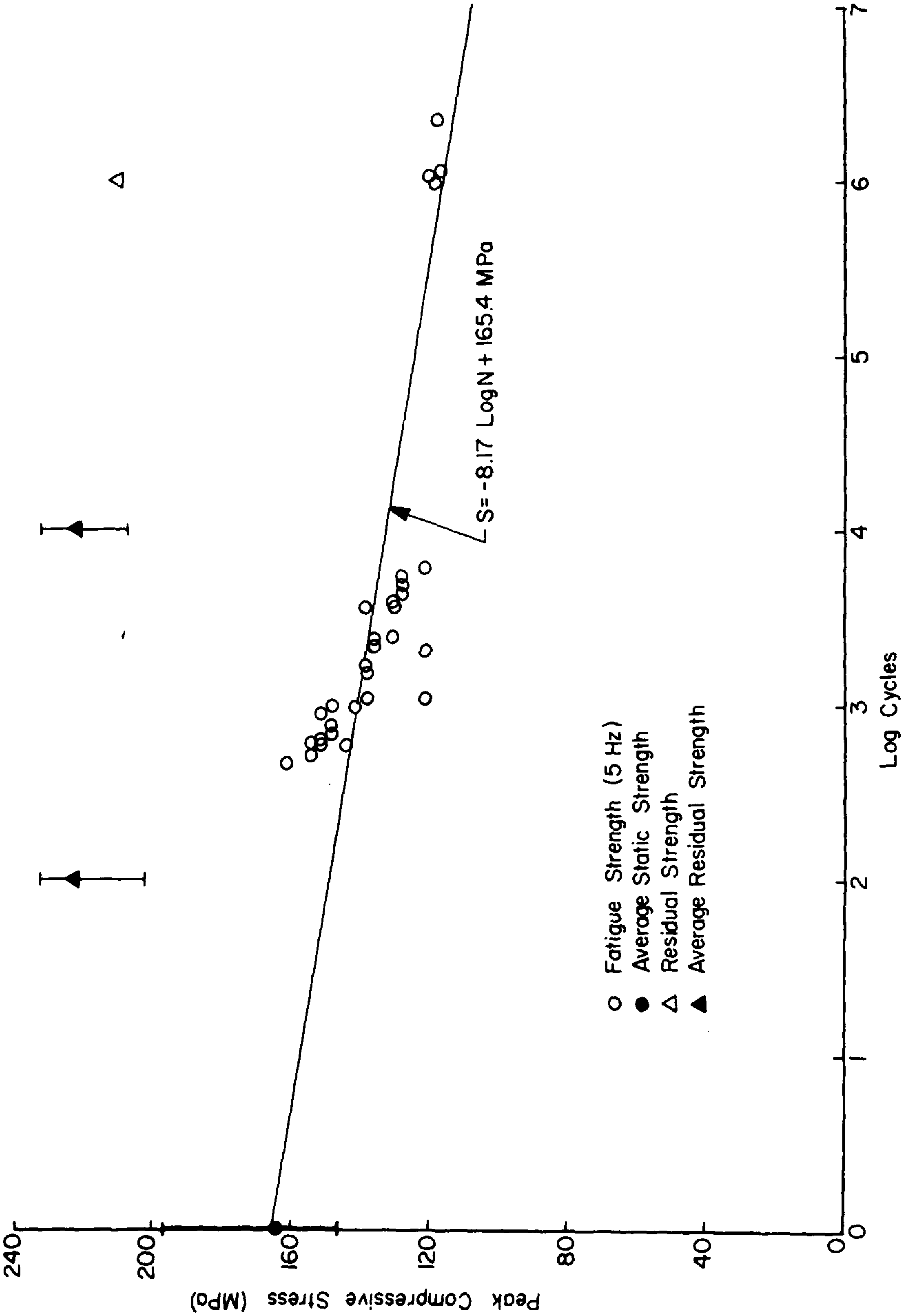

FIGURE 6
Compression Static and Fatigue Strengths

possibly due to a relaxation of end effect stress concentrations and even internal stresses during cycling, which would result in a residual strength after cycling which is greater than the static strength.

3.3 Torsion Static Results

It was originally intended to obtain the shear S-N fatigue behavior of the Hercules 3501-6 epoxy also, by performing a series of torsion fatigue tests. However, it was discovered that the lowest loading range of the Instron Model 1321 testing machine which was available was not low enough to accurately test the 6.3 mm (0.25 in) diameter specimens which had been fabricated. Thus, the torsion fatigue tests could not be completed and only static test results are available. In future work, use of larger diameter specimens will resolve this problem.

Static torsion shear tests were performed on both dry and moisture-preconditioned specimens. Average results for these tests are presented in Table. 1. The complete data are included in Table B-4 of Appendix B.

TABLE 1

Average Static Shear Properties of Hercules 3501-6 Epoxy Resin

Preconditioning Environment	Shear Strength (MPa)	(ksi)	Shear Modulus (GPa)	(Msi)
Dry	105	15.2	2.1	0.31
65°C, 98% R.H.	80	11.6	1.7	0.24

Shear stresses for these tests were corrected for nonlinearity in the torque versus angle of twist curves. The equations used to calculate the shear stresses and shear strains are:

$$\tau = \frac{1}{2\pi r^3}\left(3T + \theta\frac{dT}{d\theta}\right)$$

$$\gamma = \frac{r\theta}{L}$$

where
τ = shear stress
γ = shear strain
T = applied torque
θ = angle of twist
r = specimen radius
L = gage length

The derivation of these equations is presented in Reference [11].

As can be seen in Table 1, absorbed moisture caused a reduction in shear strength from 105 MPa (15.2 ksi) to 80 MPa (11.6 ksi), a reduction of approximately 24 percent. Shear modulus was reduced approximately 23 percent, from 2.1 GPa (0.31 Msi) to 1.7 GPa (0.24 Msi).

For an isotropic material, the Poisson's ratio ν can be calculated from the tensile Young's modulus E and the shear modulus G by the relation:

$$\nu = \frac{E}{2G} - 1$$

Inserting the values of Young's modulus and shear modulus (4.5 GPa and 2.1 GPa) obtained from dry test specimens, a Poisson's ratio of 0.071 is calculated, far lower than the expected value of around 0.3. Performing the same calculation for the wet preconditioning data (4.4 GPa and 1.7 GPa), the Poisson's ratio is 0.29, closer to the expected value. The dry shear modulus value is probably slightly high. It should also be noted that the calculation of Poisson's ratio by this manner is very sensitive to slight variations in the moduli values.

SECTION 4

FAILURE SURFACE EXAMINATIONS

Failed static test specimens were mounted and gold coated for examination in the University of Wyoming scanning electron microscope (SEM) in an effort to identify the failure mode for each of the three loading types.

Most tension specimens failed in an irregular shape, as shown in Figure 7, where the loading direction was top-to-bottom on the specimen. Two distinctly different failure surfaces were noted in the regions marked A and B in Figure 7.

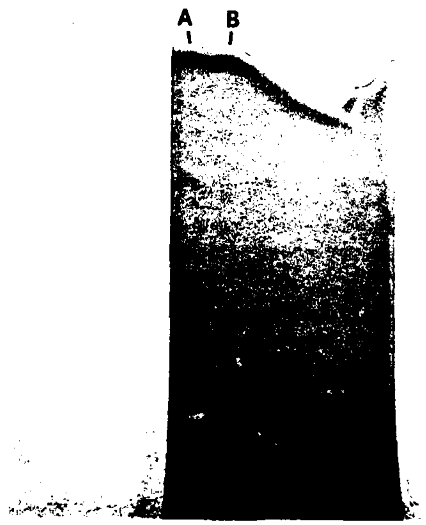

FIGURE 7

Typical Appearance of a Failed Tensile Test Specimen

Figure 8 is a 100X magnification of the region marked "A" in Figure 7. This was probably the point at which failure was initiated, thought to be a tensile mode failure.

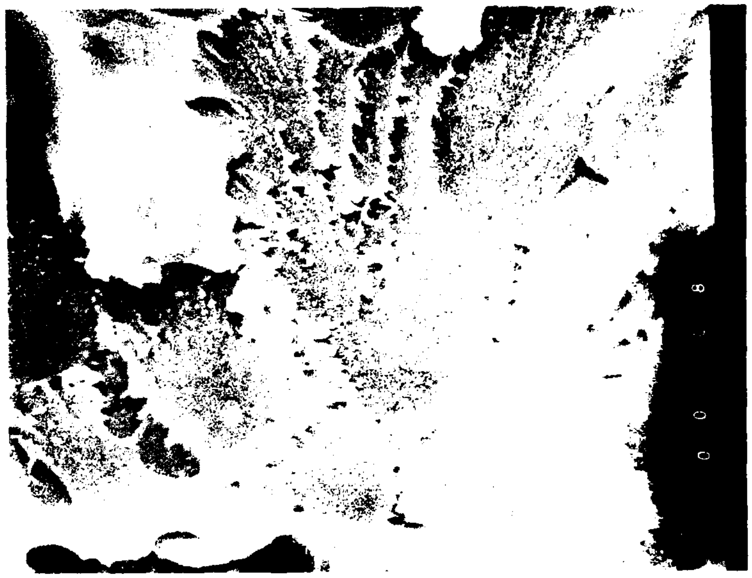

FIGURE 8

Tensile Failure Surface From Region A in Figure 7, 100X

Region "B" from Figure 7 is shown in Figure 9, magnified 100X. At this point the appearance of the failure surface changed from that shown in Figure 8 to the rippled appearance shown in Figure 9. It would appear that failure due to tensile loading could be a mixed mode, probably due to combined tension and shear.

FIGURE 9

Tensile Failure Surface From Region B of Figure 7, 100X

Torsion failure surfaces as shown in Figure 10 exhibited rippled features similar to those previously shown (in Figure 9) for tension. The photograph for Figure 10 was taken near the edge of the solid rod specimen, which would be the point of maximum shear stress in a torsion test. The circular edge of the specimen is evident in Figure 10. However, torsion specimens failed in spiral fractures on angled planes which would indicate tension failure modes to be important.

Compression failures were on planes at approximately 45° angles from the loading direction (the planes of maximum shear stress), indicating a probable shear failure mode. In examining the failed compression

FIGURE 10

Torsion Shear Specimen Failure Surface, 100X

specimens, the same rippled appearance was observed as was seen in torsion and tensile specimens. A compression failure surface is shown in Figure 11.

From the failure surface examinations it would appear that the compression specimens failed in a primarily shear-dominated mode, as would be intuitively expected. Tensile specimens failed due to a tensile failure mode, but some evidence of a second failure mode was also present. Torsion specimens exhibited the same rippled failure surface as seen in the tension and compression specimens. However, it is not clear whether this is due to tensile or shear stresses or a combination of both.

FIGURE 11

Compression Specimen Failure Surface, 300X

SECTION 5

DISCUSSION

Stress states within each of the three types of specimens may be compared by use of the simple Mohr's circle representation, as shown in Figure 12. The measured strength value for each test has also been marked on the circle for each particular loading mode. The tension specimens failed at an average stress of 59 MPa (8.5 ksi), which would induce a shear stress of approximately 29 MPa (4.3 ksi). These specimens showed two types of failure surface, but failure appeared to initiate at a tensile mode site. Torsional shear specimens failed at an average shear stress of 105 MPa (15 ksi), which would induce principal tensile and compressive stresses of the same magnitude, i.e., 105 MPa. Compressive stresses of 164 MPa (24 ksi), shown in the third circle, would induce a shear stress of 82 MPa (12 ksi). The shear values indicated for torsional shear and compression loading are fairly close, indicating shear failure is probably the primary failure mode. Failure surfaces for torsion and compression loading were similar also. However, comparing the tension loading results to those of torsion loading, it would appear that a torsion specimen should fail in a tensile mode. Perhaps the failures in the tensile specimens which appeared to initiate in a tensile mode were caused by some local flaw which acted as a stress concentration, making the tensile strength appear to be small. No visible flaws were evident in the specimens; however, microscopic flaws were undoubtedly present.

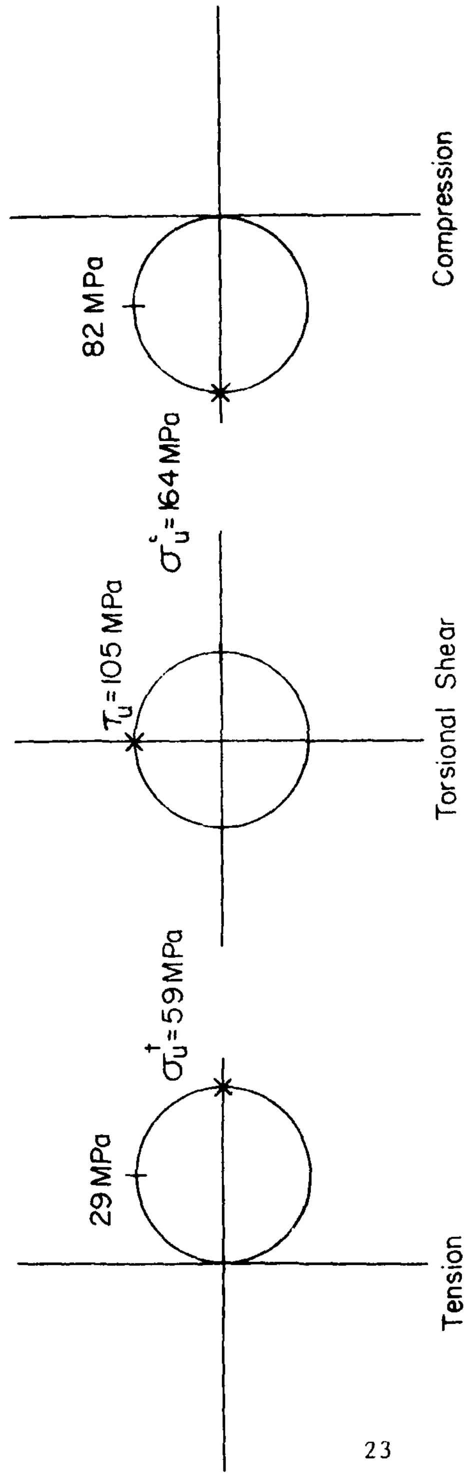

FIGURE 12

Mohr's Circle Representations of the Three Applied Stress States (X Denotes Average Measured Strength)

SECTION 6

CONCLUSIONS

This initial study of the static and fatigue properties of Hercules 3501-6 epoxy resin resulted in the following conclusions:

1. Hercules 3501-6 epoxy resin can be cast to form test specimens of consistently good quality. However, this fabrication is more art than science at this time.
2. Fatigue S-N behavior for tension-tension and compression-compression loading modes is of the form $S = A \log N + B$.
3. Tensile fatigue strength of dry specimens decreases from an average static value of 59 MPa (8.5 ksi).
4. Tensile fatigue strength of moisture-preconditioned specimens decreases at the same rate as in dry specimens, but at a peak stress level which is approximately 20 percent less than that for dry tensile specimens. Static shear strength is also reduced approximately 20 percent by absorbed moisture.
5. Compression fatigue strength decreases from a static average of 164 MPa (23.8 ksi) at a rate which is more rapid than for tension-tension fatigue strength.
6. The static torsional shear strength under room temperature, dry conditions is 105 MPa (15.2 ksi).
7. The static torsional shear strength of the moisture-preconditioned neat resin is 80 MPa (11.6 ksi).
8. Tension cycling appears to decrease tensile residual strength in both dry and moisture-preconditioned test specimens.

9. Compression cycling did not decrease the residual strength, but in fact caused a slight increase in residual strength.

10. End loading effects are an important consideration in compression fatigue tests. A specimen with a reduced gage section might be a better selection for future work.

11. Cycling rate appears to be very important in tension-tension fatigue, higher cyclic rates leading to shorter fatigue lives.

12. Similar failure mode sites were present in all specimens examined, for all loading conditions, and failure modes are occurring under some static loading conditions. More failure analysis is needed, including the analysis of fatigue failure surfaces.

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APPENDICES

APPENDIX A

NEAT RESIN CASTING PROCEDURE

This procedure was used to make all of the neat resin castings used in this research program. Three different molds were used to cast plates, or the two diameters of solid rods. All molds were vertical standing steel split molds. Neat resin plates were cast vertically between steel plates to allow bubbles to rise to an edge and to maintain a consistent thickness.

Two different ovens were required during the procedure, a vacuum oven and an air circulating oven. Unless otherwise stated, heating of molds and resin was carried out in the air circulating oven to maintain consistent, even temperatures. The casting procedure is as follows:

1. In a shallow wide pan, melt the required quantity of resin in a vacuum oven (no vacuum yet).
2. When the resin is melted, begin pulling a vacuum. The resin will tend to foam and over-flow the pan, this can be controlled by partially releasing the vacuum, still continuing to pump.
3. Continue to maintain vacuum until the resin bubbles break and the foam subsides. The resin, although still bubbling, will be clear. Release the vacuum.
4. Pour the resin into a mold preheated to 100°C. At this point the resin should be very viscous. If it is not, sufficient volatiles were not removed during vacuum and will be present as bubbles in the final casting. Because the resin flows so slowly, it is helpful

to use some type of filling reservoir (a funnel works well) to let the resin flow into the mold. Filling the mold must be done at 100°C, in either type of oven; the resin will stop flowing or solidify if cooled.

5. Once the mold has been filled, place it in the air circulating oven and increase the temperature to 150°C for 1 hour.
6. Final cure is accomplished at 177°C for 3 hours. Specimens may then be removed from the molds and postcured if so desired. No postcuring was done on specimens used in this program.

Several pitfalls exist which could interfere with successful molding. First, all equipment should be kept clean; acetone works well for disolving uncured resin. Release agents must be used on the steel molds to prevent adherence of the resin; however, excess release agents will outgas, forming bubbles in the casting. It helps to bake the molds at 150°C or so after applying release agents. Two release agents were used in this procedure, Miller-Stephenson MS-122, and Frekote 33. Finally, a degree of patience is required; even with practice, only 60-80 percent of the moldings produced specimens deemed suitable for testing.

APPENDIX B

INDIVIDUAL TEST RESULTS

TABLE B-1

TENSILE STATIC AND FATIGUE DATA-DRY SPECIMENS (NO PRECONDITIONING)

Test Type	Peak Stress (MPa)	Peak Stress (ksi)	Cycles To Failure	Elastic Modulus (GPa)	Elastic Modulus (ksi)
Static	50.6	7.34	1	4.7	0.69
(2 mm/min)	57.2	8.30	1	4.8	0.70
	67.7	9.82	1	3.9	0.56
Average	58.5	8.49		4.5	0.65
Fatigue	56.7	8.22	23		
(5 Hz)	52.6	7.63	56		
	51.3	7.44	325		
	49.9	7.23	1,607		
	43.5	6.31	3,266		
	41.0	5.95	3,614		
	49.4	7.17	4,901		
	37.9	5.50	28,531		
	37.4	5.43	34,388		
	40.1	5.81	39,655		
	34.8	5.04	84,520		
	31.4	4.55	211,866		
	27.9	4.05	1,260,201		
Cyclic Rate Effect Tests					
15 Hz	40.7	5.90	1,550		
15 Hz	40.7	5.90	2,050		
30 Hz	40.7	5.90	190		
30 Hz	40.7	5.90	370		

Residual Strength Tests	Peak Stress (MPa)	Peak Stress (ksi)	Cycles	Residual Strength (MPa)	Residual Strength (ksi)
(5Hz)	42.7	6.19	100	53.0	7.68
(2 mm/min)	42.7	6.19	100	58.5	8.48
	42.7	6.19	100	63.6	9.23
	42.7	6.19	100	65.2	9.46
Average				60.1	8.71
	33.0	4.78	10,000	41.0	5.95
	33.0	4.78	10,000'	43.7	6.34
	33.0	4.78	10,000	46.8	6.79
Average				43.9	6.36
	23.3	3.38	1,000,000	63.8	9.25

TABLE B-2

TENSILE STATIC AND FATIGUE DATA-MOISTURE PRECONDITIONED SPECIMENS
(65°C, 98% R.H. FOR 6 MONTHS)

Test Type	Peak Stress (MPa)	Peak Stress (ksi)	Cycles To Failure	Elastic Modulus (GPa)	Elastic Modulus (ksi)
Static (2 mm/min)	34.6	5.02	1	4.1	0.59
	41.1	5.96	1	4.8	0.70
	47.1	6.83	1	3.9	0.56
	49.3	7.15	1	4.4	0.64
	54.6	7.92	1	4.7	0.69
Average	45.3	6.58		4.4	0.64
Fatigue (5 Hz)	43.1	6.25	4		
	36.2	5.26	10		
	31.7	4.60	20		
	22.7	3.29	45		
	27.2	3.95	935		
	29.4	4.27	3,597		
	18.1	2.63	8,658		
	22.7	3.29	22,063		
	15.9	2.30	332,391		
	13.6	1.97	1,072,214+		

Residual Strength Tests	Peak Stress (MPa)	Peak Stress (ksi)	Cycles	Residual Strength (MPa)	Residual Strength (ksi)
(5 Hz)	22.1	3.20	100	46.2	6.70
(2 mm/min)	22.1	3.20	100	49.9	7.24
Average				48.1	6.97
	17.9	2.60	10,000	30.1	4.36
	17.9	2.60	10,000	34.3	4.98
Average				32.2	4.67

TABLE B-3

COMPRESSION STATIC AND FATIGUE DATA-DRY SPECIMENS (NO PRECONDITIONING)

Test Type	Peak Stress (MPa)	Peak Stress (ksi)	Cycles To Failure	Residual Strength (GPa)	Residual Strength (ksi)
Static	146	21.2	1		
(2mm/min)	146	21.2	1		
	152	22.1	1		
	178	25.8	1		
	197	28.6	1		
Average	164	23.8			
Fatigue	161	23.3	488		
(5Hz)	154	22.4	503		
	154	22.4	549		
	151	21.9	585		
	144	20.9	587		
	154	22.4	590		
	151	21.9	605		
	144	20.9	668		
	148	21.4	776		
	151	21.9	885		
	141	20.5	990		
	148	21.4	990		
	138	20.0	1,145		
	121	17.6	1,185		
	138	20.0	1,514		
	139	20.1	1,738		
	121	17.6	2,020		
	136	19.7	2,093		
	131	19.0	2,310		
	136	19.7	2,338		
	130	18.8	3,581		
	139	20.1	3,627		
	130	18.8	3,758		
	128	18.6	4,280		
	128	18.6	4,890		
	127	18.4	5,250		
	121	17.6	6,110		
	118	17.1	984,890		
	118	17.1	1,009,452		
	120	17.4	1,066,000		
	117	16.9	1,073,020		
	118	17.3	2,261,000		

TABLE B-3 (Continued)

COMPRESSION STATIC AND FATIGUE DATA-DRY SPECIMENS (NO PRECONDITIONING)

Test Type	Peak Stress (MPa)	Peak Stress (ksi)	Cycles To Failure	Residual Strength (GPa)	Residual Strength (ksi)
Residual Strength	120	17.4	100	202	29.3
	120	17.4	100	232	33.6
	120	17.4	100	232	33.7
Average				222	32.2
	106	15.4	10,000	206	29.9
	106	15.4	10,000	222	32.2
	106	15.4	10,000	223	32.3
	106	15.4	10,000	232	33.6
Average				221	32.0
	92	13.4	1,000,000	210	30.5

TABLE B-4

STATIC TORSIONAL SHEAR DATA

Preconditioning Environment	Strength (MPa)	Strength (ksi)	Elastic Shear Modulus (GPa)	Elastic Shear Modulus (Msi)
Dry	108	15.7	2.2	0.32
	108	15.7	2.1	0.31
	105	15.2	2.2	0.32
	96	14.3	2.0	0.29
Average	105	15.2	2.1	0.31
65°C	79	11.5	1.7	0.24
98% R.H.	81	11.7	1.7	0.24
6 month exposure	79	11.4	1.7	0.24
	79	11.5	1.7	0.25
	81	11.8	1.6	0.23
Average	80	11.6	1.7	0.24

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