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Ten-Year Ground Exposure of Composite Materials Used on the Bell Model 206L Helicopter Flight Service Program

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Abstract

Residual strength results are presented for four composite material systems that have been exposed for up to 10 years to the environment at five different locations on the North American Continent. The exposure locations are near where the Bell Model 206L helicopters, which participated in a flight service program sponsored by NASA Langley Research Center and the U.S. Army, were flying in daily commercial service. The composite material systems are (1) Kevlar-49 fabric/F-185 epoxy; (2) Kevlar-49 fabric/LRF-277 epoxy; (3) Kevlar-49 fabric/CE-306 epoxy; and (4) T-300 graphite/E-788 epoxy. Six replicates of each material were removed and tested after 1, 3, 5, 7, and 10 years of exposure. The average baseline strength was determined from testing six as-fabricated specimens. More than 1700 specimens have been tested. All specimens that were tested to determine their strength were painted with a polyurethane paint. Each set of specimens also included an unpainted panel for observing the weathering effects on the composite materials. A statistically based procedure has been used to determine the strength value above which at least 90 percent of the population is expected to fall with a 95-percent confidence level. The computed compression strengths are 80 to 89 percent of the baseline (no-exposure) strengths. The resulting compression strengths are approximately 8 percent below the population mean strengths. The computed short-beam-shear strengths are 83 to 92 percent of the baseline (no-exposure) strengths. The computed tension strength of all materials is 93 to 97 percent of the baseline (no-exposure) strengths.

Introduction

The influence of moisture on the long-term strength and stiffness of advanced composite materials and aircraft components made from these materials is an on-going concern of aircraft designers and manufacturers. As a result of moisture and other operational concerns, NASA Langley Research Center and the U.S. Army initiated flight and ground-based environmental effects programs to assess the performance of advanced composite materials and structures subjected to normal operating environments. Primary and secondary structural components have been in service on transport aircraft since the early 1970's. The first major helicopter flight service program, initiated in 1978, included the installation of three Kevlar-49[1]/epoxy components and one graphite/epoxy component on the Bell Model 206L helicopter. These components were Federal Aviation Administration (FAA) certified and flown in commercial service. Because most helicopters spend a considerable portion of their service life on or near the ground, a series of coupon tests were performed to assess the long-term effects of ground-based environments on the composite materials used on the Bell Model 206L components. The locations selected for the ground-based specimen exposure sites are in the general areas where the composite components are being flown in service.

This paper presents a summary of residual strength test results of all specimens that have been exposed for up to 10 years. Detailed test results for specimens that have been exposed for 7 and 10 years are included in the appendix. Detailed results for specimens exposed for the first 5 years of the 10-year program are presented in reference 1.

Exposure Specimens

Coupon specimens have been exposed at five locations on the North American Continent, as shown in figure 1. The selected areas include a hot, humid, salt-spray environment (Cameron, Louisiana, and an offshore oil platform in the Gulf of Mexico), a cold environment (Fort Greely, Alaska); a cold, damp, pollution-prone environment (Toronto, Canada); and a mild, humid environment (Hampton, Virginia). The selected locations are in the general areas where helicopters with the composite components are being flown in service. Each location contains one rack, as shown in figure 2. The racks were installed

[1]Kevlar-49 is a registered trademark of E. I. du Pont de Nemours & Co., Inc.

in 1980, and each rack contains five trays of specimens. A tray of specimens contains 24 each of tension, short-beam-shear (SBS) and Illinois Institute of Technology Research Institute (IITRI) compression specimens and four 2.0-in-wide specimens to provide information on weathering characteristics of each material system. The tension, compression, and SBS specimens were painted with a polyurethane paint (IMIRON[2]) that is used on the flight service helicopters. Specimen geometry is given in reference 1.

The four composite material systems in the ground exposure program are as follows: (1) Kevlar-49 fabric (style 281)/F-185[3] epoxy $[0_f/45_f/0_f]_s$; (2) Kevlar-49 fabric (style 120)/ LRF-277[4] epoxy $[0_f/90_f/\pm 45_f]_s$; (3) Kevlar-49 fabric (style 281)/CE-306[5] epoxy $[0_f/90_f]_s$; and (4) T-300 graphite[6]/E-788[7] epoxy $[0/\pm 45/0]_s$. The F-185 and the LRF-277 are 250°F cure epoxy systems. The CE-306 is a 250°F cure epoxy system that was cured at 200°F for 5 hr for this application. The E-788 is a 350°F cure epoxy. Style 281 Kevlar-49 fabric, which is a plain weave fabric with 17 ends/in. of 1140 denier yarn in each direction, has a weight of 5.0 oz/yd^2. Style 120 Kevlar-49 fabric, which is a plain weave fabric with 34 ends/in. of 195 denier yarn in each direction, has a weight of 1.8 oz/yd^2.

The specimens used for moisture determination were cut from the tested tension specimens. A 0.5-in-long section was cut from the undamaged area of the tension specimens as soon as possible after test completion. The paint was removed by sanding, using caution not to remove an excessive amount of the outer ply. Each specimen was weighed after the paint was removed. A 0.5-in-long specimen was also removed from the unpainted exposure specimens and weighed prior to being used for moisture determination. All specimens were stored in sealed plastic bags between different operations.

Test Methods

Each tray of specimens was in a sealed plastic bag when it was received at NASA Langley Research Center. The trays remained in the sealed bag until testing was initiated. All tests were performed at room temperature on six replicates for each specimen type. The tests were performed in accordance with the following American Society for Testing and Materials (ASTM) standards (ref. 2): (1) Tension–D3039-(76); (2) SBS–D2344-(76); and (3) Compression–D3410-(75) using the IITRI test fixture.

The specimens used for moisture determination were placed in a vacuum oven at 140°F. Each specimen was weighed periodically to determine weight loss as a function of drying time.

Data Analysis

Statistically based mechanical properties have been defined for each of the materials used in this environmental exposure program. A procedure for determining statistically based mechanical properties for composite materials is detailed in MIL-HDBK-17-1C (ref. 3). The material used in the exposure program will not meet all the requirements of MIL-HDBK-17-1C because a minimum of five lots of material were required in the data sample, and initial material inspection requirements were added to the handbook after this environmental exposure program was initiated. Although all the requirements of MIL-HDBK-17-1C cannot be maintained, a final mechanical property value can be determined. At least 90 percent of the population of values is expected to exceed this final value with a 95-percent confidence interval. This final value is normally considered the B-basis value. For this report, the B-basis value will be called B-value because all the requirements in MIL-HDBK-17-1C for a B-basis value cannot be fulfilled. A step-by-step method for selecting the appropriate computational method is outlined in MIL-HDBK-17-1C, and this method contains procedures that evaluate several different statistical models and determines which model, if any, adequately describes the data. The procedures include methods for detecting outliers, testing the compatibility of several batches of data, and investigating the form of the underlying population from which a sample is drawn.

A flowchart of the statistical procedure used in the present report is shown in figure 3, and a step-by-step statistical procedure for data analysis is as follows:

1. The sample data should be visually inspected for observations that are suspected of being outliers. Each sample is analyzed to determine potential outliers using the maximum "normed" residual outlier test. The computed

[2]IMIRON is a trademark of E. I. du Pont de Nemours & Co., Inc.

[3]F-185 is manufactured by Hexcel Corporation.

[4]LRF-277 is manufactured by Brunswick Corporation.

[5]CE-306 is manufactured by Ferro Corporation.

[6]T-300 is manufactured by Ammoco Performance Products, Inc.

[7]E-788 is manufactured by U.S. Polymetric Company.

statistic is compared with the critical statistic for the sample size at a 0.05 significance level. If the computed statistic is greater than the critical value, the data are reviewed for possible errors; otherwise, go to the next step.

2. The k-sample Anderson-Darling test is used to test the hypothesis that the mechanical property data from different samples are independent random samples of the same population. The calculated test statistic is compared with the critical value for the sample size at a 0.05 significance level. If the test statistic is less than the critical value, the samples should be treated as a single population, and the pooled data should be checked for outliers (step 4). If the calculated test statistic is equal to or greater than the critical value, it is concluded that the samples are not identically distributed, and the equality-of-variance test (step 3) should be performed.

3. The equality-of-variance test is used to test the hypothesis that the variances of the populations from which two or more independent random samples were taken are equal. The computed statistic is compared with the 0.95 quantile of a chi-square distribution. If the test does not reject the hypothesis that the variances are equal, then the one-way analysis of variance random effects method (ANOVA) should be used to compute the B-value. If the test is rejected, then a currently approved method for computing the B-value allowables does not exist. If this occurs, the sources of variability should be investigated.

4. The pooled data should also be visually inspected for observations suspected of being outliers. The pooled data are analyzed with the statistical outlier procedure (step 1) using a significance level of 0.05 to identify potential outliers. If the test indicates that outliers may exist, the data should be checked for possible errors; otherwise, go to the next step.

5. The pooled data are analyzed to determine the best fit to several statistical distributions. These tests yield an observed significance level (OSL) for each of the distributions. The OSL measures the probability of observing an Anderson-Darling statistic as extreme as the value that is calculated by assuming that the given distribution is the correct one. The test is applied sequentially to the two-parameter Weibull, normal, and lognormal distributions. If the OSL is greater than 0.05, the distribution tested should be used to compute the B-value. If none of the OSL tests exceeds 0.05, a nonparametric procedure is used to compute the B-value.

The first assumption for determining the statistically based strength is to assume that the population of data includes the baseline data and all the exposure data for each material system. Each sample of the population is considered to be the data from one exposure site at one exposure time. This approach will give a population of 120 data points from 20 samples.

Results and Discussion

The exposure racks at Hampton, Virginia, Toronto, Canada, and Ft. Greely, Alaska (fig. 1), have been exposed to ground conditions for 10 years. The exposure racks at Cameron, Louisiana, and on the offshore oil platform in the Gulf of Mexico were exposed for 3 years before being lost to hurricanes in 1985. All data shown for 1 and 3 years of exposure are from five exposure sites, and data for 5, 7, and 10 years of exposure are from the three remaining sites. The paint on the specimens maintained its integrity for the duration of the program. The baseline strengths for the as-fabricated specimens are given in reference 1.

Residual Compression Strength

Compression tests of the composite materials were conducted using the IITRI specimen to determine the effect of exposure and exposure site on the residual compression strength. The mean compression failure strength and the standard deviation for each exposure time and exposure site are given in tables 1 through 4. The residual compression strength as a function of the exposure time and the exposure location are presented in figures 4 through 7. The residual strength shown in the figures is the ratio of the mean failure stress to the mean baseline compressive strength for the material. Each figure also shows the scatter band in baseline strength for each material.

Kevlar-49/F-185. Residual compression strength results for Kevlar-49/F-185 epoxy material are shown in figure 4. The effects of exposure location (fig. 4) indicate an 11-percent variation in strength after 1 year of exposure, a 7-percent variation after 3 years of exposure, and a 3-percent variation after 10 years of exposure. The material exposed at Ft. Greely, Alaska, had the lowest strength for all exposure times. The average strength for all exposure sites indicated a 3-percent loss for 1 year of exposure; this loss increased to an 8-percent loss for 10 years of exposure.

The statistical procedure just noted was applied to all the data for Kevlar-49/F-185 material tested in compression. No outliers were observed in any of the 20 samples. The computed Anderson-Darling statistic of 2.91 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 18.88, which is less than the critical value of 30.14. The within-samples variances are not significant for the 0.05 significance level; thus, the ANOVA method was used to compute the B-value of 17.7 ksi. This value and the minimum, maximum, and standard deviation values for the population are given in table 5.

Kevlar-49/LRF-277. Residual compression strength results for the Kevlar-49/LRF-277 epoxy material are shown in figure 5. These results indicate a 6- to 17-percent reduction in strength after 1 year of exposure, and they also show that approximately the same strength loss was maintained for the remainder of the exposure time. The effect of exposure site location accounted for approximately a 10-percent difference in the strength loss. After 7 years of exposure, the material exposed at Hampton, Virginia, had a maximum strength loss of 17 percent, while the material exposed at Toronto, Canada, exhibited a minimum strength loss of 8 percent. The statistical procedure was applied to all the Kevlar-49/LRF-277 material tested in compression. No outliers were observed in any of the 20 samples. The computed Anderson-Darling statistic of 2.52 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed statistic for the equality-of-variance test is 24.84, which is less than the critical value. Because the within-samples variances are not significant for the 0.05 significance level, the ANOVA method was used to compute the B-value of 17.8 ksi. The B-value and the minimum, maximum, and standard deviation values for the population are given in table 5.

Kevlar-49/CE-306. Residual compression strength results for Kevlar-49/CE-306 epoxy material are shown in figure 6. These results indicate a 2-percent loss in average strength after 1 year of exposure, and they show an increase to 4 percent after 10 years of exposure. The effect of exposure location site was evident after 1 and 3 years of exposure (with the strengths varying 11 percent each). The statistical procedure was applied to all the material tested in compression. One outlier was indicated in a sample of data. This outlier is within the maximum, and minimum values of the total population. The computed Anderson-Darling statistic of 1.56 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 18.87, which is less than the critical value of 30.14. Since the within-samples variances are not significant for the 0.05 significance level, the ANOVA method was used to compute the 16.3 ksi B-value. The B-value and the minimum, maximum, and standard deviation values for the population are given in table 5.

T-300/E-788. Residual compression strength results for the T-300 graphite/E-788 epoxy material are shown in figure 7. The results do not indicate any significant trends with exposure time. The average residual strength loss did not exceed 6 percent. Specimens removed after 3 years of exposure indicated a 10-percent variance caused by exposure location, and the variance of specimens at other exposure times ranged from 2 to 7 percent. The statistical procedure was applied to all the material tested in compression. Two outliers were indicated in two different samples. Further investigation indicated that both outliers were within the minimum and maximum values of the total population. The computed Anderson-Darling statistic of 1.57 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 23.04, which is less than the critical value of 30.14. Since the within-samples variances are not significant for the 0.05 significance level, the ANOVA method was used to compute the 111.0 ksi B-value. The B-value and the minimum, maximum, and standard deviation values for the population are given in table 5.

The compression strengths of the exposed materials have been determined by a statistical procedure defined in MIL-HDBK-17-1C to determine the B-value allowables of composite materials. The resulting strengths, designated B-values, are 80 to 89 percent of the baseline (no-exposure) strengths. The resulting strengths are approximately 8 percent below the mean strengths.

Residual Short-Beam-Shear Strength

Short-beam-shear (SBS) tests of the composite materials were conducted to determine the effects of exposure and exposure site on the residual SBS strength. The mean SBS strength and the standard deviation for each exposure time and exposure site are given in tables 6 through 9. The residual SBS strength as a function of the exposure time and the exposure location are presented in figures 8 through 11. The residual strength shown in the figures is the ratio of the mean failure stress to the mean baseline SBS strength for the material type.

Kevlar-49/F-185. Residual SBS strength results for Kevlar-49/F-185 epoxy material are shown in figure 8. The effects of exposure location indicate a 10-percent variation in strength at 1 and 5 years of exposure, while the variability was 3 to 5 percent for the other exposure times. The average loss of strength after 10 years of exposure was 5 percent. No significant trends were observed during the exposure time. The statistical procedure just noted was applied to all the data for Kevlar-49/F-185 material tested for SBS strength. Three outliers were determined in three different samples. Two of the outliers were within the data limits for the population. The other outlier determined the minimum data value for the population, and it is approximately 0.4 ksi lower than the next data value. Review of the test data did not indicate a reason for these data to be excluded from the population. The computed Anderson-Darling statistic of 1.92 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 51.28, which is greater than the critical value of 30.14. These data have failed the equality-of-variance test. The within-samples variances are significant for the 0.05 significance level. The MIL-HDBK-17-1C currently does not have an approved method for computing the B-value when the equality-of-variance test fails. Passing the equality-of-variance test is one of the assumptions required for the ANOVA method. The MIL-HDBK-17-1C suggests that the ANOVA method can often be applied successfully when this assumption is not met. Using the ANOVA method, the B-value computed is 5.40 ksi, and it and the minimum, maximum, and standard deviation values for the population are shown in table 10. The computed value of 5.40 ksi is acceptable at 92 percent of the population mean.

Kevlar-49/LRF-277. Residual SBS strength results for the Kevlar-49/LRF-277 epoxy material are shown in figure 9 as a function of the exposure time and the exposure location. The results shown in figure 9 indicate a 3- to 16-percent reduction in strength during the first 7 years of exposure. After 7 years of exposure, the material exposed at Hampton, Virginia, had a maximum strength loss of 16 percent. The average strength loss was a maximum at 12 percent after 7 years of exposure. The statistical procedure was applied to all of the Kevlar-49/LRF-277 material tested for SBS strength. One outlier was observed in one of the 20 samples. The outlier, which determined the minimum data value for the population, is 0.18 ksi lower than the next data value. Review of the test data did not indicate a reason for this outlier to be excluded for the population. The computed Anderson-Darling statistic of 2.40 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed statistic for the equality-of-variance test is 17.96, which is less than the critical value. Because the within-samples variances are not significant for the 0.05 significance level, the ANOVA method was used to compute the B-value of 3.21 ksi. The B-value and the minimum, maximum, and standard deviation values for the population are given in table 10.

Kevlar-49/CE-306. Residual SBS strength results for Kevlar-49/CE-306 epoxy material are shown in figure 10 as a function of the exposure time and the exposure location. The specimens for 10 years of exposure at Ft. Greely, Alaska, were not returned with the tray of specimens and could not be located. Therefore, this data set contains only 19 samples and 114 specimens. The data indicate an 11-percent variation caused by exposure location for 1, 3, and 7 years of exposure. No significant trends are evident and most of the data fell within the scatter band for the baseline specimens. The statistical procedure was applied to all of the material tested for SBS strength. No outliers were indicated in 19 samples of data. The computed Anderson-Darling statistic of 1.54 exceeded the critical value of 1.29; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 14.42, which is less than the critical value of 28.87. Since the within-samples variances are not significant at the 0.05 significance level, the ANOVA method was used to compute the 4.68 ksi B-value. The B-value and the minimum, maximum, and standard deviation for the population are given in table 10.

T-300/E-788. Residual SBS strength results for the T-300/E-788 graphite/epoxy material are shown in figure 11 as a function of the exposure time and the exposure location. The results do not indicate any significant trends with the exposure time or the exposure location. The average residual strength is equal to or exceeds the baseline average strength. The variation caused by location is between 5 and 10 percent. The statistical procedure was applied to all the T-300/E-788 material tested for SBS strength. Two outliers were indicated in two different samples. Further investigation indicated that both outliers were within the minimum and maximum values of the total population. The computed Anderson-Darling statistic of 1.35 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 30.49, which is greater than the critical value of 30.14. These data have failed the equality-of-variance test; therefore, the within-samples variances are significant for the 0.05 significance level. The MIL-HDBK-17-1C does not currently have an approved method for computing the B-value when the equality-of-variance test fails. Passing the equality-of-variance test is one of the assumptions required for the ANOVA method. The MIL-HDBK-17-1C suggests that the ANOVA method can often be applied successfully when this assumption is not met. Using the ANOVA method, the B-value computed is 10.3 ksi, and it is shown in table 10 with the minimum, maximum, and standard deviation values for the population. The computed B-value of 10.3 ksi is acceptable at 88 percent of the population mean.

The SBS strengths of the exposed materials have been determined by a statistical procedure defined in MIL-HDBK-17-1C to determine the B-value allowables of composite materials. The resulting strengths, designated B-values, are 83 to 92 percent of the baseline (no-exposure) strengths. The resulting strengths are 8 to 10 percent below the mean strengths.

Residual Tension Strength

Tension tests were conducted on the composite materials to determine the effect of exposure time and exposure site on the residual tension strength. The mean tension strength and the standard deviation for each exposure time and exposure site are given in tables 11 through 14. The effect of exposure location and the exposure time on the residual tension strength of each material is presented in figures 12 through 15. Each figure also includes the scatter band for the specimens tested to determine the baseline strength. The residual strength shown in the figures is the ratio of the mean failure stress to the mean baseline tension strength for the material type.

Kevlar-49/F-185. Residual tension strength results for Kevlar-49/F-185 epoxy are shown in figure 12. All the average strengths of the exposed specimens are within the baseline scatter band. No significant trends were observed during the exposure time. The statistical procedure noted above was applied to all the data for Kevlar-49/F-185 material tested in tension. Four outliers were determined in three different samples. Two of the outliers were within the data limits for the population. The other outliers were the minimum and the next lowest value for the population. Review of the test data did not indicate a reason for these data to be excluded from the population. The computed Anderson-Darling statistic of 1.67 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality-of-variance test is 65.95, which is greater than the critical value of 30.14. These data have failed the equality-of-variance test. The within-samples variances are significant for the 0.05 significance level. The MIL-HDBK-17-1C does not currently have an approved method for computing the B-value when the equality-of-variance test fails. Passing the equality-of-variance test is one of the assumptions required for the ANOVA method. The MIL-HDBK-17-1C suggests that the ANOVA method can often be applied successfully when this assumption is not met. Using the ANOVA method, the B-value computed is 55.5 ksi, and it and the minimum, maximum, and standard deviation values for the population are shown in table 15. The computed value of 55.5 ksi is acceptable at 94 percent of the population mean.

Kevlar-49/LRF-277. Residual tension strength results for the Kevlar-49/LRF-277 epoxy material are shown in figure 13 as a function of the exposure time and the exposure location. No significant trends were observed during the exposure time. The statistical procedure was applied to all the Kevlar-49/LRF-277 material. One outlier was observed in one of the 20 samples. The outlier was within the maximum and the minimum of the population. Review of the test data did not indicate a reason for this outlier to be excluded for this population. The computed Anderson-Darling statistic of 1.12 is less than the critical value of 1.28; therefore, the test is not significant for the 0.05 level. The batch distributions are not significantly different, and the samples should be treated as a single sample. Two outliers were indicated in the pooled data. These outliers are the two lowest values in the pooled data. Review of the pooled data does not indicate a reason that these two points should be excluded from the population. The goodness-of-fit test of the pooled data for the two-parameter Weibull distribution yielded an OSL of 0.839. The computed B-value from the two-parameter Weibull distribution is 79.1 ksi. The B-value and the minimum, maximum, and standard deviation values for the population are given in table 15.

Kevlar-49/CE-306. Residual tension strength results for Kevlar-49/CE-306 epoxy are shown in figure 14 as a function of the exposure time and the exposure location. No significant trends are evident, and all the average strengths for the exposed specimens fall within the scatter band for the baseline specimens. The statistical procedure was applied to all the Kevlar-49/CE-306 material tested in tension. One outlier was indicated in the 20 samples of data. This outlier is within the bounds of the total population of data. The computed Anderson-Darling statistic of 1.45 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality of variance is 30.51, which is greater than the critical value of 30.14. These data have failed the equality-of-variance test; therefore, the within-samples variances are significant for the 0.05 significance level. Using the ANOVA method, as recommended by MIL-HDBK-17-1C, the B-value computed is 58.9 ksi, and it and the minimum, maximum, and standard deviation values for the population are shown in table 15. The computed value of 58.9 ksi is acceptable at 95 percent of the population mean.

T-300/E-788. Residual tension strength results for the T-300/E-788 graphite/epoxy material are shown in figure 15 as a function of the exposure time and the exposure location. The results do not indicate any significant trends with exposure time. The average residual strength is equal to or exceeds the baseline average strength. The statistical procedure was applied to all of the T-300/E-788 material tested in tension. One outlier was indicated in one sample. Further investigation indicated that the outlier was within the minimum and maximum values of the total population. The computed Anderson-Darling statistic of 1.74 exceeded the critical value of 1.28; therefore, the sample distributions differ significantly. The computed test statistic for the equality of variance is 30.96, which is greater than the critical value of 30.14. These data have failed the equality-of-variance test; therefore, the within-samples variances are significant for the 0.05 significance level. Using the ANOVA method, as recommended by MIL-HDBK-17-1C, the B-value computed is 117 ksi, and it and the minimum, maximum, and standard deviation values for the population are shown in table 15. The computed value of 117 ksi is acceptable at 91 percent of the population mean.

The tensile strengths of the exposed materials have been determined by a statistical procedure defined in MIL-HDBK-17-1C to determine the B-value allowables of composite materials. The resulting strengths, designated B-values, are 93 to 97 percent of the baseline (no-exposure) strengths. The resulting residual strengths are 6 to 9 percent below the mean strengths.

Moisture Absorption

The amount of moisture that composite materials absorb is a function of matrix and fiber type, temperature, relative humidity, and exposure conditions. The objective of these tests is to determine the moisture absorption of composite materials when exposed to various outdoor real-time environments. A summary of moisture absorption as a fraction of the composite specimen weight for painted specimens that were exposed for 3 to 10 years is tabulated in table 16 and shown in figures 16 through 19. Each data point for the painted specimens (open symbols) shown in the figures is the average of six replicates. A solid line connects the average moisture absorption data points for each set of data. Kevlar/epoxy materials absorb four to five times more moisture than graphite/epoxy materials because the Kevlar fibers absorb moisture. The cause for the reduction in moisture absorption at the tenth year is not evident. A number of reasons could cause the reduction in moisture absorption, such as drought for a few months prior to removal and improper handling in the drying process. In general, the average values of moisture absorption compare well with published values for moisture absorption by other Kevlar/epoxy and graphite/epoxy material systems (ref. 4).

A summary of the moisture absorption for unpainted material specimens is given in table 17 and shown in figures 16 through 19. Each data point (filled symbol) for the unpainted material is from a single specimen. A dashed line connects the average moisture absorption data points for the unpainted specimens for each exposure time. The Kevlar-49/F-185 material absorbs approximately 0.5 percent more moisture when painted. Paint on the other Kevlar-49 material systems does not have a significant effect on the moisture absorption. The painted T-300/E-788 graphite/epoxy material absorbs approximately 0.1 percent more moisture than the unpainted system.

Weathering

The effects of weathering on bare composite specimens that were exposed at Hampton, Virginia, are shown in figures 20 through 23. Each figure shows the as-fabricated, 1-year, 3-year, 5-year, 7-year, and 10-year exposed specimens. The photographs shown in these figures are a 15X magnification of the exposed surface. The as-fabricated and 1-year exposure views for Kevlar-49/F-185 material shown in figure 20 indicate that the surface fibers are coated with resin. Some resin has been lost during the 1 year of exposure, as noted by the reduced definition of the peel ply pattern. The 3-year exposure view has parts of the surface ply yarns exposed because of the weathering of the surface layer epoxy. Epoxy still remains in the valleys between the yarn crimps. After 5 years of exposure, all resin has been washed from the surface, and some fiber damage is evident. More damage of the surface is shown after 7 years of exposure. After 10 years of exposure, only fragments of the surface ply remain, and degradation of the second ply, a 45° ply, has started. The as-fabricated view (fig. 21) of the Kevlar-49/LRF-277 material indicates that some voids are present in the surface ply. The 1-year exposure view shows that most of the surface resin has been washed away and that a few fibers are exposed. After 3 years, all the resin has been washed from between the yarns, as shown in figure 21. Exposure for 5 through 10 years caused loss of the outer ply and considerable damage to the second ply. The Kevlar-49/CE-306 material is shown in figure 22. The photograph of the specimen after 1 year of exposure indicates that some resin has been washed away by the reduced definition of the pattern of the peel ply used in fabrication. Additional resin is lost after 3 years of exposure, thus exposing the crimped fibers as shown in figure 22. After 5 years of exposure, only small pockets of resin remain in the lowest areas. Resin is also washed from the surface of the yarns. After 7 years of exposure, all resin has been washed from the exposed surface, and some of the yarns are starting to fray. After 10 years of exposure, the fill yarns are lost from the near surface, some of the fibers from the warp yarns appear to be missing, and additional resin is also washed from between the yarns. Views of T-300/E-788 graphite/epoxy material are shown in figure 23. By the third year, the definition of the peel ply has washed away. Each succeeding exposure time through 10 years has an increasing number of bare surface fibers. The specimens exposed at the other locations have similar surface degradation. This surface degradation emphasizes the need to keep composite materials protected from elements of the environment (such as sun and rain).

Concluding Remarks

The influence of ground-based environments on the long-term durability of three Kevlar/epoxy systems and one graphite/epoxy system has been studied. Results after 10 years of ground exposure indicate that all materials exhibit good strength retention.

A statistically based procedure has been used to determine the strength value above which at least 90 percent of the population is expected to fall with a 95-percent confidence level. The resulting residual strength results are summarized as follows:

1. Compression strengths are 80 to 89 percent of the baseline (no-exposure) strengths.

2. The resulting residual strengths are approximately 8 percent below the population mean strengths.

3. Short-beam-shear strengths are 83 to 92 percent of the baseline (no-exposure) strengths. The resulting residual strengths are 8 to 10 percent below the mean strengths.

4. Tensile strengths are 93 to 97 percent of the baseline (no-exposure) strengths. The resulting residual strengths are 6 to 9 percent below the mean strengths.

The Kevlar-49/F-185 material absorbs approximately 0.5 percent more moisture when it is painted. Paint on the other Kevlar-49 material systems does not have a significant effect on moisture absorption. The painted T-300/E-788 graphite/epoxy absorbs approximately 0.1 percent more moisture than the unpainted system.

The exposed composite specimens demonstrate the need to protect unpainted composite materials from long-term environmental exposure.

NASA Langley Research Center
Hampton, VA 23681-0001
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Appendix

Detailed Test Results for Specimens With 7 and 10 Years of Environmental Exposure

This appendix presents the detailed results for all specimens that have been removed after 7 and 10 years of exposure. The results are from exposure sites at Hampton, Virginia, Toronto, Canada, and Ft. Greely, Alaska.

Residual Strength

The residual strength tables A1 through A12 in this appendix include exposure time, specimen size, failure load, and computed failure stress. The residual strengths for each material as a function of exposure time for each exposure location are added to the figures shown in reference 1 and are provided in this appendix.

Residual Compression Strength

Compression tests were conducted on specimens that have been exposed for 7 and 10 years to determine the effects of exposure and exposure site on the residual compression strength. The results of tests on the exposed compression specimens are given in the following tables and figures: table A1 and figure A1 for Kevlar-49/F-185, table A2 and figure A2 for Kevlar-49/CE-306, table A3 and figure A3 for Kevlar-49/LRF-277, and table A4 and figure A4 for T-300/E-788.

Residual Short-Beam-Shear Strength

Short-beam-shear (SBS) tests were conducted on specimens that have been exposed for 7 and 10 years to determine the effects of exposure time and exposure site on the residual SBS strength. The results of tests on the exposed SBS specimens are given in the following tables and figures: table A5 and figure A5 for Kevlar-49/F-185, table A6 and figure A6 for Kevlar-49/CE-306, table A7 and figure A7 for Kevlar-49/LRF-277, and table A8 and figure A8 for T-300/E-788. The 10-year exposure specimens at Ft. Greely, Alaska, for the Kevlar-49/CE-306 were apparently lost or removed from the rack at some unknown time.

Residual Tension Strength

Tension tests were conducted on specimens that have been exposed for 7 and 10 years to determine the effects of exposure time and exposure site on the residual tensile strength. The results of tests on the exposed tension specimens are given in the following tables and figures: table A9 and figure A9 for Kevlar-49/F-185, table A10 and figure A10 for Kevlar-49/CE-306, table A11 and figure A11 for Kevlar-49/LRF-277, and table A12 and figure A12 for T-300/E-788.

References

1. Baker, Donald J.: *Five Year Ground Exposure of Composite Materials Used on the Bell Model 206L Flight Service Evaluation.* NASA TM-101645, AVSCOM TM-89-B-007, 1989. (Available from DTIC as AD A233 549.)

2. *Space Simulation; Aerospace and Aircraft; High Modulus Fibers and Composites.* Volume 15.03 of *1992 Annual Book of ASTM Standards*, 1992.

3. Military Handbook—Polymer Matrix Composites. Volume 1, Guidelines. MIL-HDBK-17-1C, Feb. 28, 1992. (Supersedes MIL-HDBK-17-1B.)

4. Dexter, H. Benson; and Baker, Donald J.: Worldwide Flight and Ground-Based Exposure of Composite Materials. *ACEE Composite Structures Technology—Review of Selected NASA Research on Composite Materials and Structures*, NASA CP-2321, 1984, pp. 17–50.

Table 1. Mean Compression Failure Stress and Standard Deviation for Painted Kevlar-49/F-185 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	19 946	496
	3	20 354	257
LA	1	20 446	542
	3	19 333	560
VA	1	19 654	496
	3	20 423	541
	5	19 691	407
	7	18 516	936
	10	18 634	864
Can	1	19 236	459
	3	19 308	417
	5	19 421	575
	7	19 198	674
	10	18 858	571
AK	1	18 137	314
	3	18 899	438
	5	18 714	350
	7	18 278	481
	10	18 242	334

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 2. Mean Compression Failure Stress and Standard Deviation for Painted Kevlar-49/LRF-277 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	20 810	635
	3	19 140	1241
LA	1	21 052	921
	3	19 433	827
VA	1	19 925	1082
	3	20 051	1509
	5	19 359	762
	7	18 578	935
	10	19 108	1153
Can	1	19 912	520
	3	18 931	731
	5	21 134	481
	7	20 498	484
	10	20 411	540
AK	1	18 890	509
	3	20 449	512
	5	19 677	1234
	7	20 193	775
	10	19 129	559

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 3. Mean Compression Failure Stress and Standard Deviation for Painted Kevlar-49/CE-306 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	17 815	497
	3	17 796	915
LA	1	17 892	774
	3	17 488	1239
VA	1	19 153	887
↓	3	19 050	635
↓	5	18 001	679
↓	7	17 284	720
↓	10	17 615	1265
Can	1	17 583	958
↓	3	17 003	905
↓	5	17 990	517
↓	7	18 540	823
↓	10	17 900	737
AK	1	17 181	950
↓	3	17 553	592
↓	5	17 546	968
↓	7	17 856	670
↓	10	17 312	699

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 4. Mean Compression Failure Stress and Standard Deviation for Painted T-300/E-788 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	126 787	9546
	3	117 724	8282
LA	1	130 437	6510
	3	115 102	10 159
VA	1	127 956	5870
↓	3	126 062	4870
↓	5	125 195	8091
↓	7	118 892	6247
↓	10	122 649	4627
Can	1	127 306	3489
↓	3	123 921	7234
↓	5	127 357	5210
↓	7	120 341	4553
↓	10	123 005	7795
AK	1	121 310	6664
↓	3	119 694	5739
↓	5	128 974	13 000
↓	7	116 211	7734
↓	10	120 087	3783

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 5. Compression Strength After Environmental Exposure

[All values for properties shown are in ksi]

Property	Material			
	Kevlar-49/F-185	Kevlar-49/LRF-277	Kevlar-49/CE-306	T-300/E-788
Mean	19.3	20.0	17.8	123
Minimum	17.1	17.0	15.6	106
Maximum	21.4	23.8	20.8	141
Standard Deviation	.878	1.22	.932	7.80
B-value	17.7	17.8	16.3	111
Distribution	ANOVA	ANOVA	ANOVA	ANOVA

Table 6. Mean Short-Beam-Shear Failure Stress and Standard Deviation for Painted Kevlar-49/F-185 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	5717	116
	3	6011	271
LA	1	5908	43
	3	5992	234
VA	1	6130	134
↓	3	6188	233
	5	5923	364
	7	5730	228
	10	5761	308
Can	1	5789	356
↓	3	5955	293
	5	6062	172
	7	5918	186
	10	5610	419
AK	1	5565	242
↓	3	5908	210
	5	5495	220
	7	5975	149
	10	5805	113

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 7. Mean Short-Beam-Shear Failure Stress and Standard Deviation for Painted Kevlar-49/LRF-277 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	3501	109
	3	3384	143
LA	1	3594	109
	3	3384	143
VA	1	3756	90
	3	3505	86
	5	3493	115
	7	3241	104
↓	10	3586	202
Can	1	3662	93
	3	3496	102
	5	3738	200
	7	3575	145
↓	10	3532	83
AK	1	3395	125
	3	3710	208
	5	3381	94
	7	3510	167
↓	10	3566	186

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 8. Mean Short-Beam-Shear Failure Stress and Standard Deviation for Painted Kevlar-49/CE-306 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	5157	229
	3	5239	437
LA	1	5156	236
	3	4916	234
VA	1	5378	265
	3	5413	265
	5	5200	271
	7	5436	213
↓	10	5204	206
Can	1	5503	314
	3	5244	478
	5	5041	344
	7	4879	348
↓	10	5216	189
AK	1	4892	245
	3	5495	167
	5	5030	224
	7	5355	396
↓	10		

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 9. Mean Short-Beam-Shear Failure Stress and Standard Deviation for Painted T-300/E-788 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	11 443	638
	3	11 642	279
LA	1	11 320	689
		11 387	692
VA	1	11 412	460
↓	3	11 686	505
	5	11 562	824
	7	11 654	882
	10	11 431	598
Can	1	11 254	708
↓	3	11 968	707
	5	11 648	936
	7	11 789	664
	10	11 851	756
AK	1	10 389	321
↓	3	11 034	702
	5	10 772	558
	7	11 666	416
	10	10 822	1339

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 10. Short-Beam-Shear Strength After Environmental Exposure

[All values for properties shown are in ksi]

Property	Material			
	Kevlar-49/F-185	Kevlar-49/LRF-277	Kevlar-49/CE-306	T-300/E-788
Mean	5.87	3.55	5.21	11.4
Minimum	4.78	3.04	4.44	9.32
Maximum	6.57	4.05	5.89	12.8
Standard Deviation	.287	.193	.328	.719
B-value	5.40	3.21	4.68	10.3
Distribution	ANOVA[a]	ANOVA	ANOVA	ANOVA

[a]Material did not meet all necessary requirements.

Table 11. Mean Tension Failure Stress and Standard Deviation for Painted Kevlar-49/F-185 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	57 826	2115
	3	59 227	1686
LA	1	58 549	1636
	3	59 198	2357
VA	1	60 050	2798
↓	3	60 773	1057
↓	5	59 950	933
↓	7	60 941	462
↓	10	56 754	1164
Can	1	59 567	2540
↓	3	60 247	1342
↓	5	59 547	1250
↓	7	59 187	1498
↓	10	58 171	4714
AK	1	58 941	5090
↓	3	60 062	1309
↓	5	60 732	699
↓	7	60 312	1574
↓	10	57 114	993

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 12. Mean Tension Failure Stress and Standard Deviation for Painted Kevlar-49/LRF-277 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	83 055	7326
	3	85 719	3565
LA	1	86 507	4303
	3	87 021	2263
VA	1	83 981	3763
↓	3	86 055	6240
↓	5	88 467	2078
↓	7	88 057	2429
↓	10	81 950	5280
Can	1	86 763	2046
↓	3	87 541	2870
↓	5	80 579	2399
↓	7	87 324	5728
↓	10	86 127	3640
AK	1	85 512	5788
↓	3	83 600	4974
↓	5	88 894	2538
↓	7	86 399	3871
↓	10	85 178	3113

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 13. Mean Tension Failure Stress and Standard Deviation for Painted Kevlar-49/CE-306 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	61 382	1319
	3	61 436	2183
LA	1	61 208	1724
	3	60 452	1185
VA	1	63 859	1227
	3	63 575	556
	5	61 661	1524
	7	63 775	1723
	10	60 953	2824
Can	1	63 473	1580
	3	63 770	1268
	5	62 137	1728
	7	61 935	2904
	10	63 392	2028
AK	1	62 668	1408
	3	62 958	1557
	5	60 384	2811
	7	62 848	1554
	10	61 767	2558

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 14. Mean Tension Failure Stress and Standard Deviation for Painted T-300/E-788 After Environmental Exposure

Exposure location[a]	Exposure time, yr	Mean failure stress, psi	Standard deviation, psi
GF	1	123 086	8 012
	3	127 850	7 676
LA	1	122 772	3 163
	3	127 620	8 962
VA	1	127 927	3 503
	3	128 272	7 974
	5	130 815	3 531
	7	132 929	6 378
	10	123 580	7 407
Can	1	136 216	4 428
	3	128 551	6 057
	5	123 460	3 797
	7	137 698	5 218
	10	130 577	11 779
AK	1	126 887	12 586
	3	134 628	4 375
	5	136 193	5 601
	7	132 673	4 134
	10	130 005	4 942

[a]Locations are GF for Gulf of Mexico, LA for Cameron, Louisiana, VA for Hampton, Virginia, Can for Toronto, Canada, and AK for Ft. Greely, Alaska.

Table 15. Tension Strength After Environmental Exposure

[All values for properties shown are in ksi]

Property	Material			
	Kevlar-49/F-185	Kevlar-49/LRF-277	Kevlar-49/CE-306	T-300/E-788
Mean	59.2	85.8	62.3	129
Minimum	48.6	70.7	57.2	108
Maximum	65.2	94.3	66.9	146
Standard Deviation	2.38	4.20	2.10	7.60
B-value	55.5	79.1	58.9	117
Distribution	ANOVA[a]	Weibull	ANOVA[a]	ANOVA[a]

[a]Material did not meet all necessary requirements.

Table 16. Percent Weight Loss of Painted Specimens After Exposure

[All values are average of six data points]

(a) Percent weight loss of Kevlar-49/F-185 and Kevlar-49/LRF-277

Location	Weight loss, percent, for Kevlar-49/F-185 with exposure time, yr, of—				Weight loss, percent, for Kevlar-49/LRF-277 with exposure time, yr, of—			
	3	5	7	10	3	5	7	10
Toronto, Canada	2.23	2.60	2.47	2.39	2.03	2.20	2.29	2.16
Hampton, VA	2.42	2.76	2.64	2.50	1.81	2.24	2.40	2.24
Gulf of Mexico	2.61				1.92			
Cameron, LA	2.57				1.96			
Ft. Greely, AK	2.18	2.30	2.33	2.08	1.94	2.10	2.20	2.04
Average	2.40	2.55	2.48	2.32	1.93	2.18	2.30	2.15

(b) Percent weight loss of Kevlar-49/CE-306 and T-300/E-788

Location	Weight loss, percent, for Kevlar-49/CE-306 with exposure time, yr, of—				Weight loss, percent, for Kevlar-49/T-300/E-788 with exposure time, yr, of—			
	3	5	7	10	3	5	7	10
Toronto, Canada	2.07	2.20	2.08	1.96	0.54	0.71	0.70	0.73
Hampton, VA	1.74	2.29	2.30	2.12	0.51	0.76	0.65	0.76
Gulf of Mexico	1.81				0.49			
Cameron, LA	1.95				0.51			
Ft. Greely, AK	2.20	2.20	2.07	1.79	0.67	0.75	0.81	0.65
Average	1.95	2.23	2.15	1.96	0.56	0.74	0.72	0.71

Table 17. Percent Weight Loss of Unpainted Specimens After Exposure

[All values are from single data point]

(a) Percent weight loss of Kevlar-49/F-185 and Kevlar-49/LRF-277

Location	Weight loss, percent, for Kevlar-49/F-185 with exposure time, yr, of--				Weight loss, percent, for Kevlar-49/LRF-277 with exposure time, yr, of-			
	3	5	7	10	3	5	7	10
Toronto, Canada	1.60	1.90	1.88	2.01	2.01	2.40	2.26	2.39
Hampton, VA	1.69	2.05	2.14	1.99	2.71	2.11	2.44	2.33
Gulf of Mexico	2.03				2.36			
Cameron, LA	1.87				2.11			
Ft. Greely, AK	1.79	1.80	1.86	1.69	2.09	2.30	2.39	1.63
Average	1.80	1.92	1.96	1.90	2.23	2.27	2.36	2.12

(b) Percent weight loss of Kevlar-49/CE-306 and T-300/E-788

Location	Weight loss, percent, for Kevlar-49/CE-306 with exposure time, yr, of—				Weight loss, percent, for Kevlar-49/T-300/E-788 with exposure time, yr, of—			
	3	5	7	10	3	5	7	10
Toronto, Canada	1.85	1.90	1.94	1.98	0.51	0.62	0.56	0.62
Hampton, VA	1.62	1.96	2.10	2.01	.47	.60	.60	.56
Gulf of Mexico	2.03				.74			
Cameron, LA	1.97				.50			
Ft. Greely, AK	1.59	1.70	1.99	2.17	.54	.61	.69	.58
Average	1.81	1.85	2.01	2.05	0.55	0.61	0.62	0.59

Table A1. Compression Strength of Painted Kevlar-49/F-185 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
407	7	0.2623	0.0943	455	18 395
408	7	.2531	.1018	441	17 116
409	7	.2634	.0972	464	18 123
410	7	.2531	.0910	451	19 581
411	7	.2565	.0939	471	19 555
412	7	.2612	.0986	472	18 327
401	10	.2535	.0961	489	20 073
402	10	.2441	.0955	444	19 046
403	10	.2562	.1000	450	17 564
404	10	.2483	.0991	454	18 450
405	10	.2563	.0982	468	18 595
406	10	.2617	.1002	474	18 076

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
431	7	0.2533	0.0988	465	18 581
432	7	.2512	.1002	462	18 355
433	7	.2479	.0962	450	18 870
434	7	.2510	.0911	452	19 767
435	7	.2552	.0957	484	19 818
436	7	.2451	.1018	494	19 799
437	10	.2493	.0936	448	19 199
438	10	.2556	.0964	448	18 182
439	10	.2574	.1018	475	18 127
440	10	.2451	.1010	477	19 269
441	10	.2547	.0944	455	18 924
442	10	.2471	.1005	483	19 449

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
443	7	0.2461	0.1018	457	18 241
444	7	.2526	.0988	467	18 712
445	7	.2578	.0996	474	18 460
446	7	.2556	.0955	456	18 681
447	7	.2586	.1013	456	17 407
448	7	.2550	.1019	472	18 165
449	10	.2404	.1001	446	18 534
450	10	.2552	.0989	467	18 503
451	10	.2516	.1013	452	17 734
452	10	.2507	.0931	431	18 466
453	10	.2576	.0987	456	17 935
454	10	.2474	.1004	454	18 278

Table A2. Compression Strength of Painted Kevlar-49/CE-306 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
413F	7	0.2474	0.0972	414	17 216
414F	7	.2458	.0959	421	17 860
415F	7	.2574	.0981	463	18 336
416F	7	.2646	.0957	413	16 310
417F	7	.2691	.0955	440	17 121
418F	7	.2677	.0968	437	16 864
407F	10	.2579	.0986	446	17 539
408F	10	.2678	.0967	405	15 639
409F	10	.2551	.0964	459	18 665
410F	10	.2546	.0980	473	18 957
411F	10	.2497	.0997	453	18 196
412F	10	.2631	.0961	422	16 690

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
437F	7	0.2668	0.0831	437	19 710
438F	7	.2563	.0973	442	17 724
439F	7	.2662	.0957	466	18 292
440F	7	.2510	.0942	457	19 328
441F	7	.2467	.0931	424	18 461
442F	7	.2650	.0975	458	17 726
443F	10	.2477	.0973	446	18 505
444F	10	.2617	.0958	414	16 513
445F	10	.2674	.0955	458	17 935
446F	10	.2501	.1005	449	17 864
447F	10	.2563	.0958	455	18 531
448F	10	.2707	.0974	476	18 053

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
449F	7	0.2523	0.0967	445	18 240
450F	7	.2602	.0939	444	18 172
451F	7	.2387	.0982	434	18 515
452F	7	.2635	.0971	425	16 611
453F	7	.2470	.0952	420	17 861
454F	7	.2642	.0922	432	17 735
455F	10	.2660	.0951	444	17 552
456F	10	.2628	.0961	414	16 393
457F	10	.2549	.0952	432	17 802
458F	10	.2634	.0959	419	16 587
459F	10	.2598	.0952	429	17 345
460F	10	.2493	.0957	434	18 191

Table A3. Compression Strength of Painted Kevlar-49/LRF-277 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
416B	7	0.2500	0.0784	354	18 061
417B	7	.2207	.0776	320	18 685
418B	7	.2483	.0778	368	19 050
419B	7	.2277	.0767	336	19 239
420B	7	.2390	.0782	364	19 476
421B	7	.2621	.0765	340	16 957
410B	10	.2574	.0789	367	18 071
411B	10	.2565	.0781	356	17 771
412B	10	.2634	.0774	382	18 737
413B	10	.2328	.0759	367	20 770
414B	10	.2496	.0778	389	20 032
415B	10	.2333	.0772	347	19 266

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
440B	7	0.2432	0.0779	402	21 219
441B	7	.2302	.0764	359	20 412
442B	7	.2424	.0803	408	20 961
443B	7	.2368	.0782	373	20 143
444B	7	.2368	.0776	372	20 244
445B	7	.2577	.0766	395	20 010
446B	10	.2263	.0776	347	19 760
447B	10	.2229	.0786	361	20 605
448B	10	.2372	.0775	370	20 127
449B	10	.2301	.0788	365	20 130
450B	10	.2304	.0794	390	21 319
451B	10	.2505	.0780	401	20 523

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
452B	7	0.2464	0.0788	396	20 395
453B	7	.2356	.0778	384	20 950
454B	7	.2348	.0792	384	20 649
455B	7	.2510	.0779	372	19 025
456B	7	.2342	.0784	357	19 443
457B	7	.2425	.0781	392	20 698
458B	10	.2344	.0766	337	18 769
459B	10	.2465	.0771	383	20 152
460B	10	.2280	.0775	341	19 298
461B	10	.2520	.0769	370	19 093
462B	10	.2521	.0768	360	18 594
463B	10	.2553	.0793	382	18 869

Table A4. Compression Strength of Painted T-300/E-788 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
248V	7	0.2558	0.0666	2035	119 451
249V	7	.2563	.0706	2130	117 714
250V	7	.2558	.0693	2185	123 259
251V	7	.2567	.0708	2220	122 150
252V	7	.2555	.0702	1920	107 047
253V	7	.2579	.0691	2205	123 731
242V	10	.2559	.0714	2245	122 871
243V	10	.2571	.0715	2308	125 553
244V	10	.2497	.0709	2092	118 167
245V	10	.2541	.0679	2010	116 499
246V	10	.2513	.0677	2193	128 901
247V	10	.2555	.0706	2235	123 903

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
272V	7	0.2559	0.0715	2205	120 513
273V	7	.2590	.0680	2015	114 411
274V	7	.2667	.0681	2090	115 074
275V	7	.2573	.0695	2223	124 313
276V	7	.2553	.0714	2260	123 982
277V	7	.2570	.0698	2220	123 755
278V	10	.2559	.0717	2453	133 693
279V	10	.2565	.0693	2270	127 704
280V	10	.2548	.0713	2156	118 675
281V	10	.2558	.0712	2178	119 585
282V	10	.2554	.0695	2246	126 533
283V	10	.2549	.0704	2007	111 842

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
284V	7	0.2550	0.0706	1950	108 315
285V	7	.2596	.0693	2165	120 343
286V	7	.2570	.0685	1980	112 471
287V	7	.2574	.0718	2045	110 652
288V	7	.2569	.0701	2090	116 055
289V	7	.2555	.0694	2295	129 429
290V	10	.2571	.0660	2066	121 754
291V	10	.2553	.0687	2003	114 202
292V	10	.2549	.0694	2094	118 372
293V	10	.2569	.0697	2164	120 854
294V	10	.2513	.0676	2034	119 732
295V	10	.2558	.0690	2217	125 608

Table A5. Short-Beam-Shear Strength of Painted Kevlar-49/F-185 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
91	7	0.2624	0.0941	183	5559
92	7	.2606	.0941	193	5903
93	7	.2669	.1074	206	5390
94	7	.2618	.0876	179	5854
95	7	.2603	.0953	188	5684
96	7	.3047	.0986	240	5991
85	10	.2638	.1049	197	5345
86	10	.2804	.1002	202	5398
87	10	.2609	.0938	194	5955
88	10	.2598	.0950	198	6020
89	10	.2604	.0883	184	5995
90	10	.2624	.0862	177	5856

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
115	7	0.2568	0.0965	196	5932
116	7	.2593	.0938	186	5735
117	7	.2605	.0945	204	6215
118	7	.2620	.0963	192	5707
119	7	.2543	.1022	208	6002
120	7	.2625	.0947	196	5913
121	10	.2730	.0983	202	5654
122	10	.2658	.1018	173	4784
123	10	.2600	.0913	188	5952
124	10	.2499	.0933	181	5816
125	10	.2605	.0912	184	5793
126	10	.2584	.1032	201	5662

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
127	7	0.2485	0.0967	187	5836
128	7	.2624	.0945	202	6110
129	7	.2467	.0912	185	6167
130	7	.2618	.0973	201	5918
131	7	.2593	.0918	184	5797
132	7	.2574	.0900	186	6022
133	10	.2620	.0966	199	5894
134	10	.2531	.0894	170	5628
135	10	.2632	.0955	195	5809
136	10	.2620	.0898	183	5846
137	10	.2598	.0914	188	5932
138	10	.2587	.1011	200	5721

Table A6. Short-Beam-Shear Strength of Painted Kevlar-49/CE-306 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
91F	7	0.2568	0.0935	177	5529
92F	7	.2581	.0933	171	5326
93F	7	.2545	.0944	172	5369
94F	7	.2483	.0931	176	5710
95F	7	.2477	.0907	153	5108
96F	7	.2519	.0951	178	5573
85F	10	.2435	.0900	152	5185
86F	10	.2582	.0837	147	5098
87F	10	.2591	.0905	159	5092
88F	10	.2552	.0843	143	4978
89F	10	.2452	.0942	171	5559
90F	10	.2519	.0936	167	5312

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
115F	7	0.2333	0.0844	122	4647
116F	7	.2488	.0877	148	5087
117F	7	.2563	.0859	135	4599
118F	7	.2534	.0954	174	5398
119F	7	.2601	.0905	158	5034
120F	7	.2287	.0822	113	4508
121F	10	.2404	.0887	142	4980
122F	10	.2559	.0937	173	5405
123F	10	.2561	.0892	164	5394
124F	10	.2574	.0864	148	4991
125F	10	.2550	.0921	165	5272
126F	10	.2424	.0912	155	5255

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
133F	7	0.2386	0.0835	134	5044
134F	7	.2570	.0930	180	5633
135F	7	.2532	.0815	132	4808
136F	7	.2603	.0945	191	5811
137F	7	.2585	.0968	188	5638
138F	7	.2400	.0852	142	5197
127F[a]	10	.2577	.0901		
128F[a]	10	.2593	.0887		
129F[a]	10	.2575	.0925		
130F[a]	10	.2443	.0905		
131F[a]	10	.2388	.0832		
132F[a]	10	.2584	.0946		

[a]Specimens lost in service.

Table A7. Short-Beam-Shear Strength of Painted Kevlar-49/LRF-277 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
91B	7	0.2490	0.0773	85	3312
92B	7	.2446	.0778	84	3311
93B	7	.2410	.0780	82	3272
94B	7	.2440	.0775	82	3252
95B	7	.2491	.0784	85	3264
96B	7	.2483	.0796	80	3036
85B	10	.2355	.0785	92	3741
86B	10	.2420	.0783	98	3863
87B	10	.2469	.0779	94	3646
88B	10	.2469	.0773	87	3399
89B	10	.2400	.0789	84	3339
90B	10	.2427	.0769	88	3528

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
115B	7	0.2652	0.0782	98	3544
116B	7	.2451	.0781	96	3761
117B	7	.2394	.0776	88	3553
118B	7	.2387	.0786	86	3438
119B	7	.2380	.0793	86	3418
120B	7	.2507	.0777	97	3735
121B	10	.2323	.0785	83	3426
122B	10	.2500	.0770	94	3651
123B	10	.2355	.0777	87	3562
124B	10	.2480	.0770	90	3531
125B	10	.2425	.0787	91	3572
126B	10	.2399	.0773	85	3450

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
127B	7	0.2359	0.0793	93	3729
128B	7	.2387	.0781	87	3500
129B	7	.2443	.0766	91	3647
130B	7	.2405	.0769	87	3528
131B	7	.2350	.0784	83	3379
132B	7	.2310	.0803	81	3275
133B	10	.2459	.0786	91	3523
134B	10	.2469	.0770	98	3858
135B	10	.2406	.0775	89	3580
136B	10	.2380	.0775	90	3660
137B	10	.2440	.0805	91	3471
138B	10	.2408	.0786	83	3305

Table A8. Short-Beam-Shear Strength of Painted T-300/E-788 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
91V	7	0.2557	0.0709	307	12 701
92V	7	.2557	.0710	303	12 517
93V	7	.2560	.0723	255	10 333
94V	7	.2572	.0729	294	11 760
95V	7	.2521	.0714	275	11 458
96V	7	.2563	.0732	279	11 153
85V	10	.2569	.0723	265	10 680
86V	10	.2568	.0724	269	10 831
87V	10	.2570	.0710	290	11 916
88V	10	.2558	.0729	277	11 157
89V	10	.2570	.0724	280	11 274
90V	10	.2537	.0720	297	12 190

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
115V	7	0.2558	0.0733	284	11 360
116V	7	.2557	.0720	264	10 755
117V	7	.2563	.0733	303	12 096
118V	7	.2562	.0730	308	12 351
119V	7	.2562	.0728	290	11 661
120V	7	.2570	.0709	304	12 513
121V	10	.2563	.0705	275	11 402
122V	10	.2564	.0741	307	12 123
123V	10	.2563	.0720	315	12 802
124V	10	.2582	.0732	268	10 631
125V	10	.2563	.0721	303	12 281
126V	10	.2573	.0737	300	11 865

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
127V	7	0.2563	0.0728	293	11 777
128V	7	.2578	.0729	307	12 251
129V	7	.2568	.0713	293	12 002
130V	7	.2545	.0723	278	11 331
131V	7	.2558	.0724	283	11 461
132V	7	.2570	.0721	276	11 171
133V	10	.2568	.0710	227	9 317
134V	10	.2568	.0721	305	12 355
135V	10	.2556	.0722	282	11 477
136V	10	.2564	.0721	250	10 126
137V	10	.2566	.0725	236	9 518
138V	10	.2574	.0735	306	12 139

Table A9. Tension Strength of Painted Kevlar-49/F-185 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
250	7	1.0015	0.0994	6100	61 276
251	7	1.0015	.1005	6100	60 606
252	7	1.0025	.1003	6090	60 566
253	7	1.0015	.1005	6080	60 407
254	7	0.9990	.1003	6150	61 377
255	7	1.0030	.1000	6160	61 416
244	10	1.0040	.0993	5713	57 304
245	10	1.0041	.0994	5800	58 112
246	10	1.0021	.0992	5501	55 337
247	10	1.0010	.0992	5745	57 855
248	10	1.0040	.0998	5633	56 218
249	10	1.0090	.0999	5614	55 695

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
274	7	1.0035	0.1000	5850	58 296
275	7	1.0035	.1004	5775	57 319
276	7	1.0002	.1003	6200	61 802
277	7	1.0001	.1004	5950	59 257
278	7	1.0045	.1005	6000	59 434
279	7	0.9998	.1000	5900	59 012
280	10	1.0001	.1004	5960	59 357
281	10	1.0002	.1001	4898	48 921
282	10	1.0006	.1008	5893	58 427
283	10	1.0003	.1005	5961	59 296
284	10	1.0005	.1003	6223	62 013
285	10	1.0003	.1002	6115	61 010

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
286	7	1.0005	0.1000	5780	57 771
287	7	1.0005	.0999	6200	62 031
288	7	1.0004	.1005	6000	59 678
289	7	1.0004	.1002	6100	60 854
290	7	1.0003	.1003	6000	59 803
291	7	1.0003	.1004	6200	61 734
292	10	1.0005	.0990	5741	57 961
293	10	1.0001	.1004	5593	55 702
294	10	1.0004	.0999	5819	58 225
295	10	1.0007	.0990	5620	56 728
296	10	1.0020	.1004	5673	56 391
297	10	1.0007	.1003	5789	57 676

Table A10. Tension Strength of Painted Kevlar-49/CE-306 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
247F	7	0.9915	0.0923	6080	66 437
248F	7	.9908	.0978	6210	64 087
249F	7	.9891	.0913	5550	61 459
250F	7	.9848	.0921	5740	63 286
251F	7	.9923	.0961	6170	64 702
252F	7	.9961	.0985	6150	62 681
241F	10	.9960	.0982	5942	60 752
242F	10	.9864	.0980	5528	57 186
243F	10	.9870	.0913	5937	65 884
244F	10	.9944	.0981	5836	59 825
245F	10	.9938	.0971	5902	61 162
246F	10	.9733	.0905	5365	60 908

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
271F	7	0.9964	0.0994	6050	61 085
272F	7	.9942	.1000	6200	62 362
273F	7	.9934	.1008	5775	57 672
274F	7	.9946	.0991	6575	66 707
275F	7	.9993	.0980	6100	62 288
276F	7	.9989	.0989	6075	61 493
277F	10	.9842	.0987	6095	62 744
278F	10	.9866	.0970	6407	66 949
279F	10	.9780	.0918	5643	62 853
280F	10	.9867	.0980	6089	62 970
281F	10	.9937	.0990	6298	64 019
282F	10	.9884	.0976	5867	60 818

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
283F	7	0.9891	0.0962	5850	61 481
284F	7	.9906	.0982	6100	62 708
285F	7	.9904	.0995	6300	63 930
286F	7	.9875	.1014	6100	60 919
287F	7	.9923	.0990	6400	65 148
288F	7	.9906	.0979	6100	62 900
289F	10	.9861	.0901	5922	66 653
290F	10	.9912	.0966	5798	60 554
291F	10	.9931	.0864	5208	60 697
292F	10	1.0061	.0977	5839	59 402
293F	10	.9896	.0974	5889	61 097
294F	10	.9923	.0989	6104	62 198

Table A11. Tension Strength of Painted Kevlar-49/LRF-277 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
247B	7	0.9852	0.0874	7710	89 540
248B	7	.9908	.0886	7600	86 575
249B	7	.9815	.0886	7610	87 511
250B	7	.9904	.0872	7310	84 643
251B	7	1.0049	.0887	7880	88 406
252B	7	.9832	.0871	7850	91 666
241B	10	.9888	.0884	6250	71 502
242B	10	1.0007	.0851	7336	86 144
243B	10	.9836	.0895	7231	82 140
244B	10	.9927	.0868	7232	83 931
245B	10	.9829	.0866	7112	83 553
246B	10	.9828	.0847	7028	84 427

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
271B	7	0.9948	0.0877	8075	92 557
272B	7	.9878	.0878	7825	90 224
273B	7	.9785	.0862	6950	82 398
274B	7	.9914	.0876	7025	80 890
275B	7	.9948	.0884	7350	83 579
276B	7	.9886	.0885	8250	94 295
277B	10	.9975	.0874	7185	82 414
278B	10	1.0049	.0897	7488	83 071
279B	10	.9850	.0854	7526	89 468
280B	10	.9753	.0875	7404	86 760
281B	10	.9912	.0880	7310	83 806
282B	10	.9775	.0852	7599	91 243

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
283B	7	0.9827	0.0882	7100	81 916
284B	7	.9953	.0855	6900	81 083
285B	7	.9936	.0872	7600	87 717
286B	7	.9786	.0861	7550	89 606
287B	7	.9888	.0886	7850	89 604
288B	7	.9795	.0854	7400	88 465
289B	10	.9987	.0866	7358	85 076
290B	10	.9899	.0868	7672	89 289
291B	10	1.0049	.0890	7440	83 188
292B	10	.9986	.0871	7382	84 872
293B	10	.9886	.0885	7693	87 929
294B	10	.9995	.0876	7067	80 714

Table A12. Tension Strength of Painted T-300/E-788 After Environmental Exposure

(a) Specimens from exposure site at Hampton, Virginia

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
415V	7	1.0028	0.0692	9050	130 415
416V	7	.9997	.0690	9370	135 838
417V	7	.9993	.0694	8640	124 583
418V	7	.9997	.0701	9940	141 840
419V	7	.9997	.0687	9400	136 868
420V	7	1.0028	.0701	9000	128 030
409V	10	1.0039	.0708	9086	127 835
410V	10	1.0057	.0729	8939	121 925
411V	10	1.0028	.0715	9004	125 578
412V	10	1.0018	.0687	7526	109 352
413V	10	1.0043	.0711	9127	127 819
414V	10	1.0015	.0695	8977	128 972

(b) Specimens from exposure site at Toronto, Canada

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
439V	7	1.0042	0.0693	9 550	137 230
440V	7	1.0018	.0729	9 625	131 793
441V	7	1.0058	.0693	10 000	143 468
442V	7	1.0046	.0716	10 400	144 586
443V	7	1.0088	.0710	9 600	134 032
444V	7	1.0023	.0698	9 450	135 076
445V	10	1.0043	.0711	9 558	133 855
446V	10	1.0023	.0712	9 063	126 997
447V	10	.9992	.0700	9 786	139 912
448V	10	1.0007	.0695	9 614	138 234
449V	10	1.0090	.0717	7 839	108 355
450V	10	1.0010	.0682	9 292	136 110

(c) Specimens from exposure site at Ft. Greely, Alaska

Specimen number	Exposure time, yr	Width, in.	Thickness, in.	Failure load, lb	Failure stress, psi
451V	7	1.0000	0.0700	9510	135 857
452V	7	1.0093	.0705	8900	125 078
453V	7	1.0060	.0700	9400	133 485
454V	7	.9996	.0686	9000	131 248
455V	7	1.0000	.0686	9200	134 111
456V	7	.9993	.0683	9300	136 259
457V	10	1.0020	.0695	9327	133 934
458V	10	.9992	.0695	8987	129 413
459V	10	1.0053	.0701	9054	128 477
460V	10	.9997	.0695	9024	129 881
461V	10	.9998	.0686	9350	136 325
462V	10	1.0090	.0703	8654	122 003

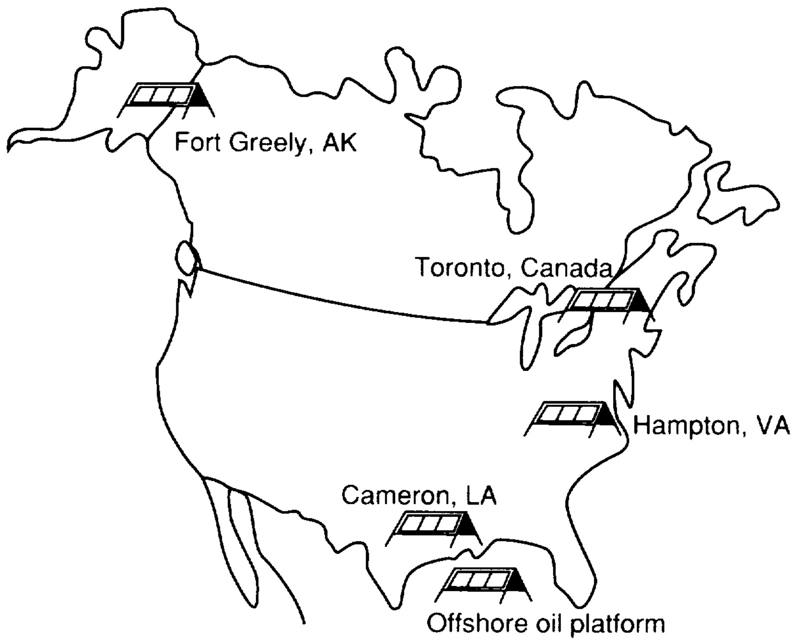


Figure 1. Location of exposure racks.

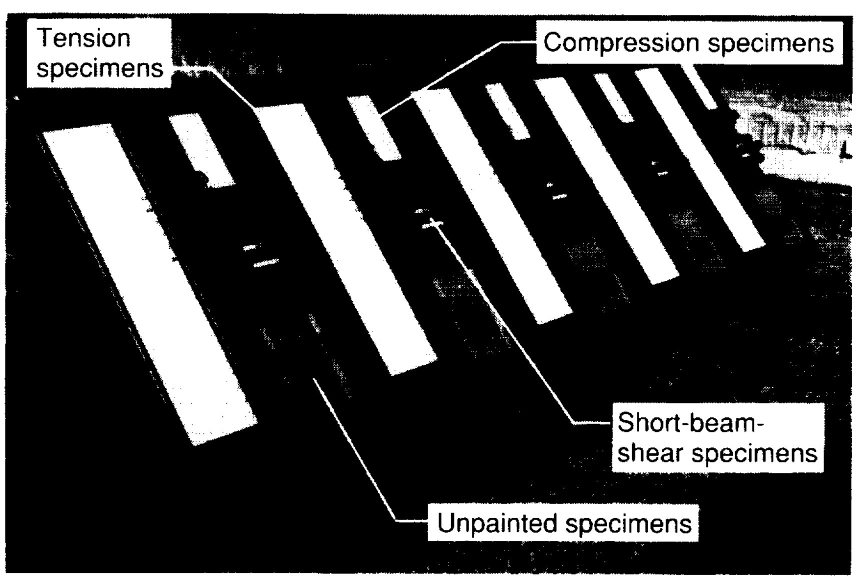


Figure 2. Photograph of exposure rack.

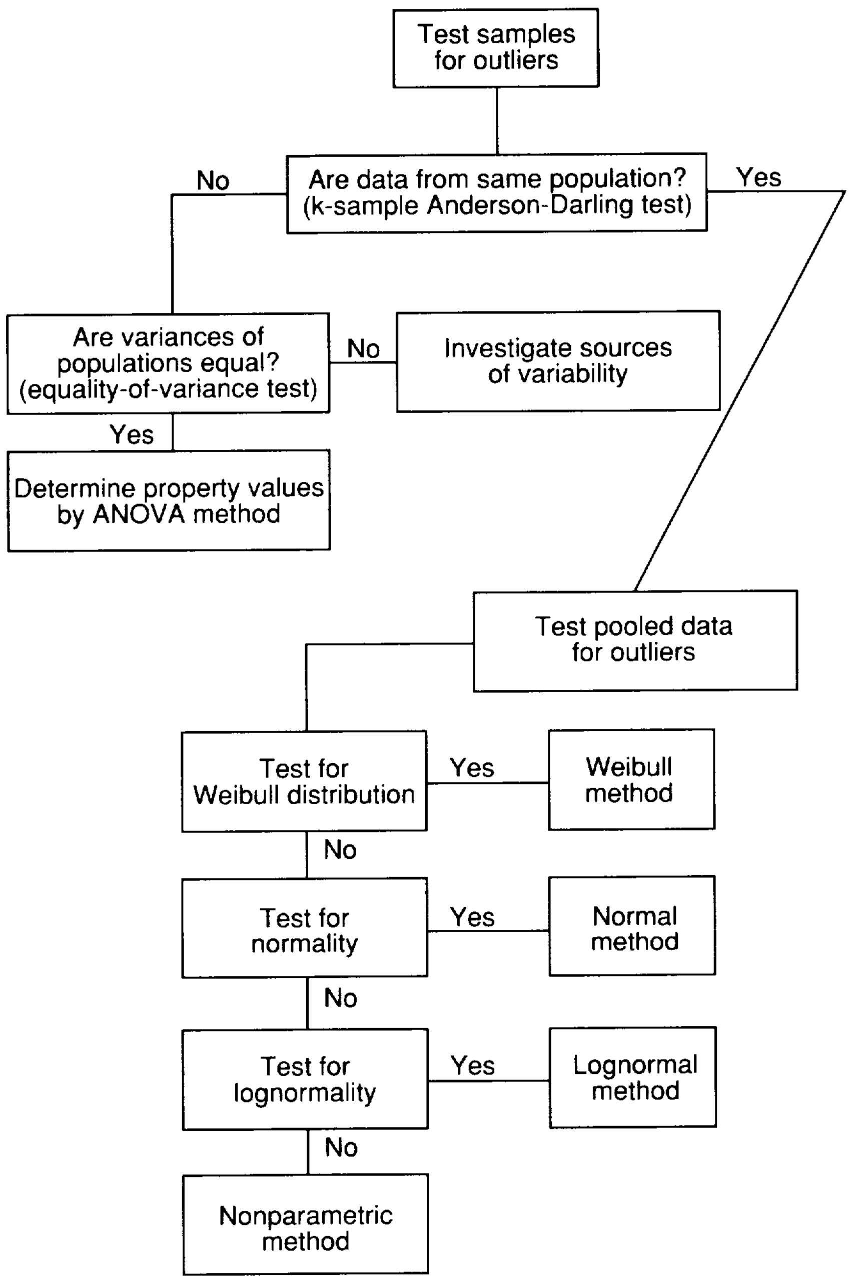


Figure 3. Flowchart of statistical procedure.

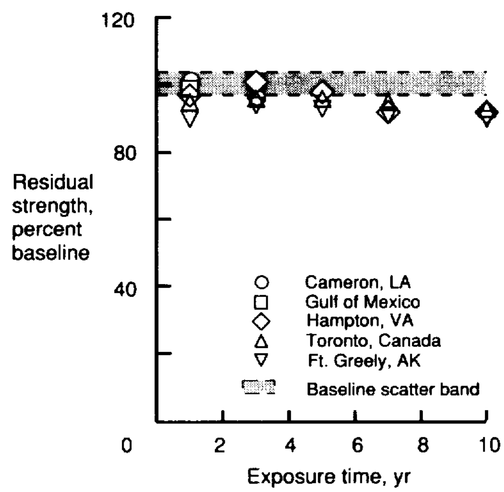


Figure 4. Effect of exposure time and location on residual compression strength of Kevlar-49/F-185.

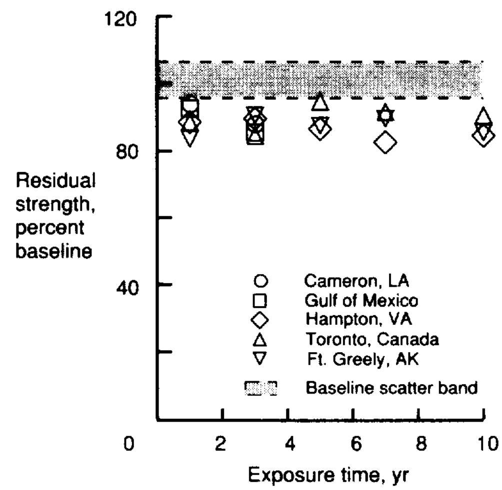


Figure 5. Effect of exposure time and location on residual compression strength of Kevlar-49/LRF-277.

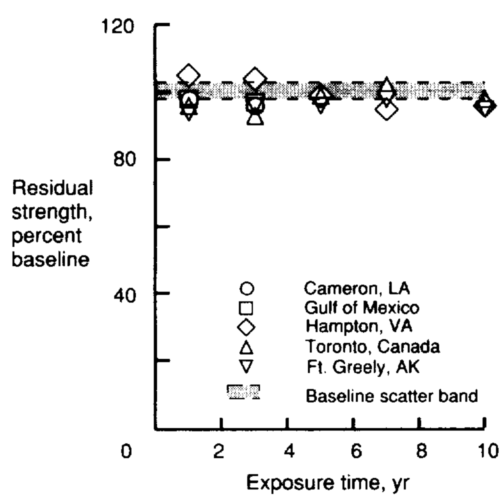


Figure 6. Effect of exposure time and location on residual compression strength of Kevlar-49/CE-306.

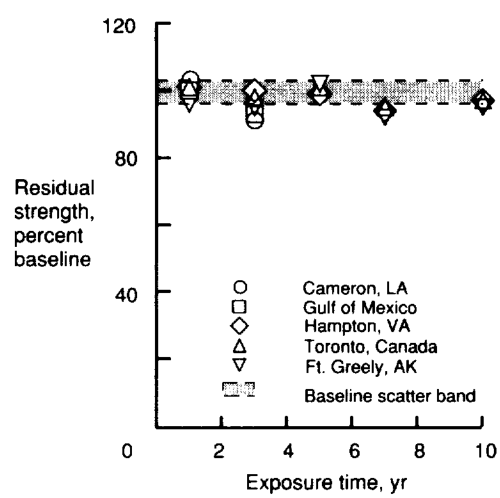
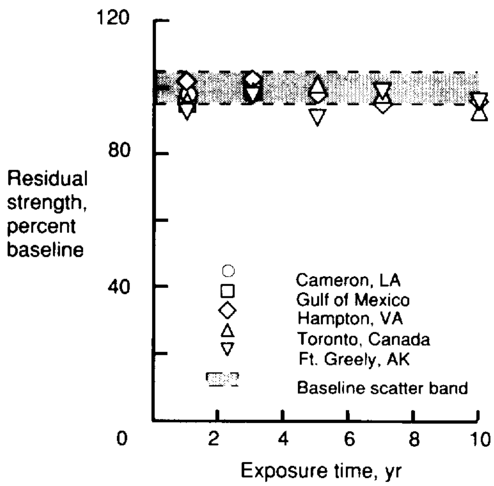


Figure 7. Effect of exposure time and location on residual compression strength of T-300/E-788.



igure 8. Effect of exposure time and location on residual SBS strength of Kevlar-49/F-185.

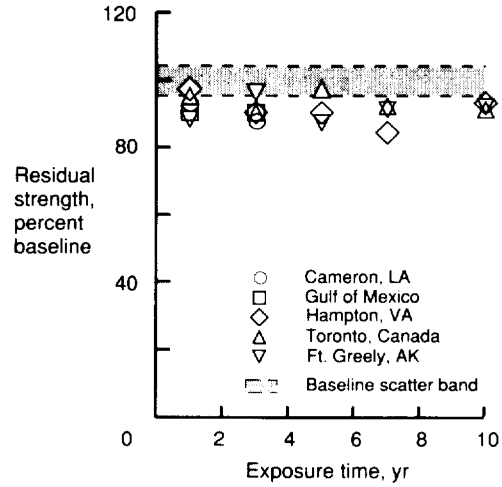
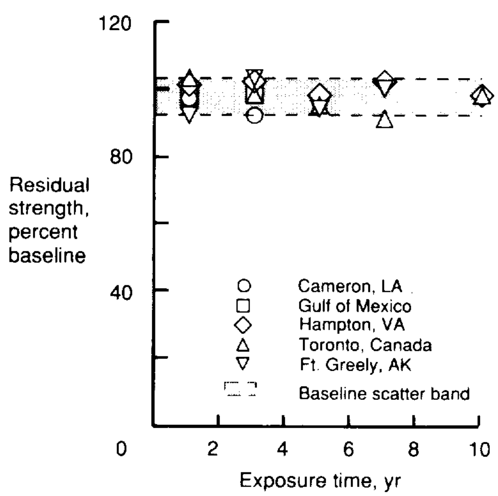


Figure 9. Effect of exposure time and location on residual SBS strength of Kevlar-49/LRF-277.



gure 10. Effect of exposure time and location on residual SBS strength of Kevlar-49/CE-306.

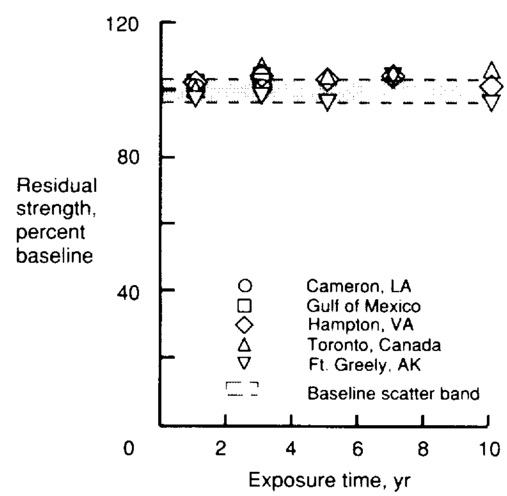


Figure 11. Effect of exposure time and location on residual SBS strength of T-300/E-788.

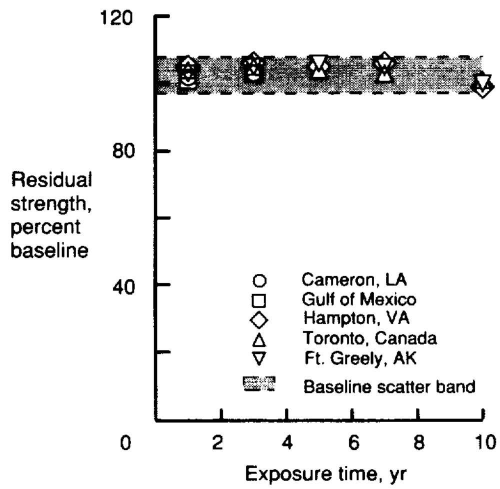


Figure 12. Effect of exposure time and location on residual tension strength of Kevlar-49/F-185.

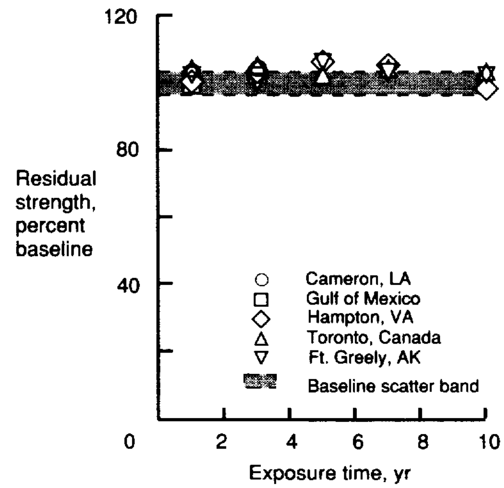


Figure 13. Effect of exposure time and location on residual tension strength of Kevlar-49/LRF-277.

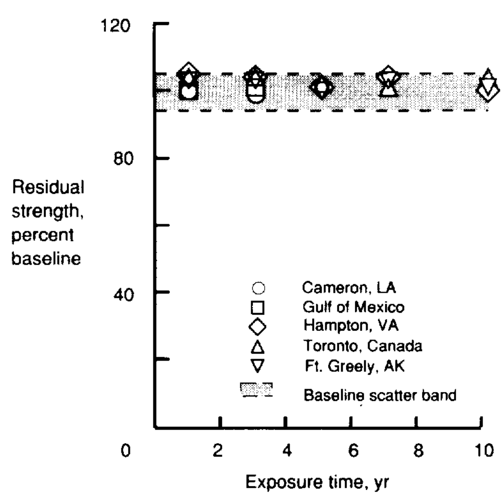


Figure 14. Effect of exposure time and location on residual tension strength of Kevlar-49/CE-306.

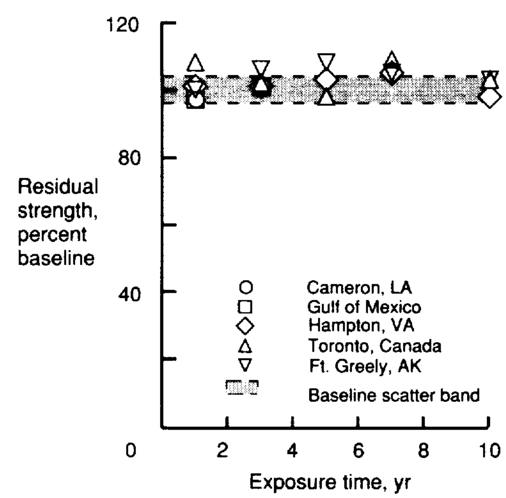


Figure 15. Effect of exposure time and location on residual tension strength of T-300/E-788.

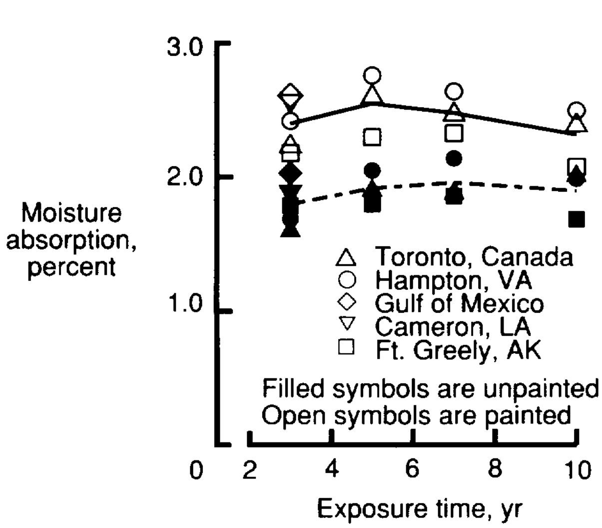


Figure 16. Moisture absorption of Kevlar-49/ F-185 composite material.

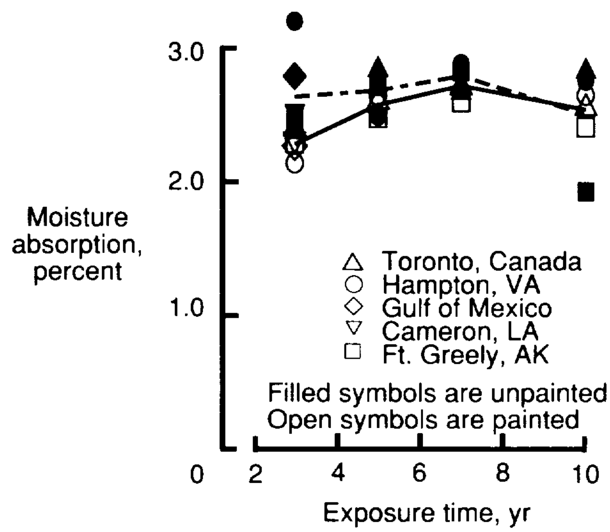


Figure 17. Moisture absorption of Kevlar-49/ LRF-277 composite material.

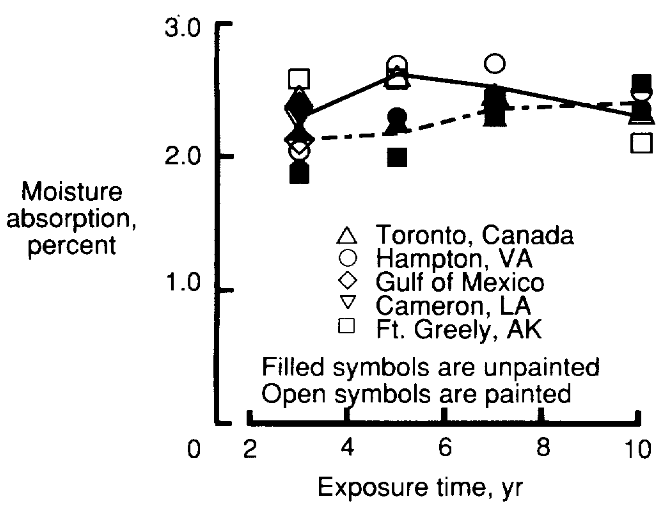


Figure 18. Moisture absorption of Kevlar-49/ CE-306 composite material.

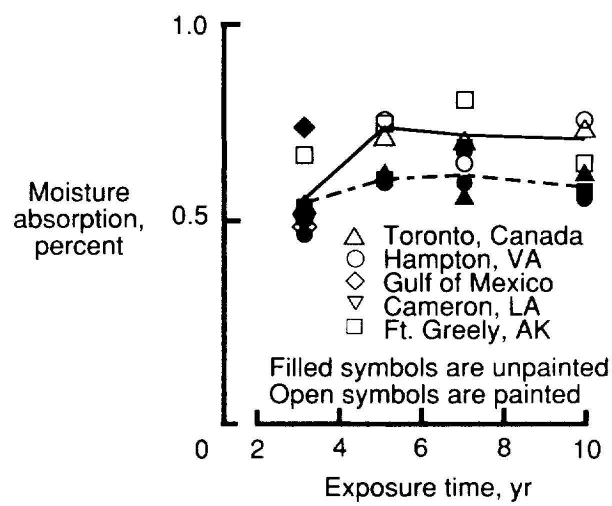


Figure 19. Moisture absorption of T-300/E-788 composite material.

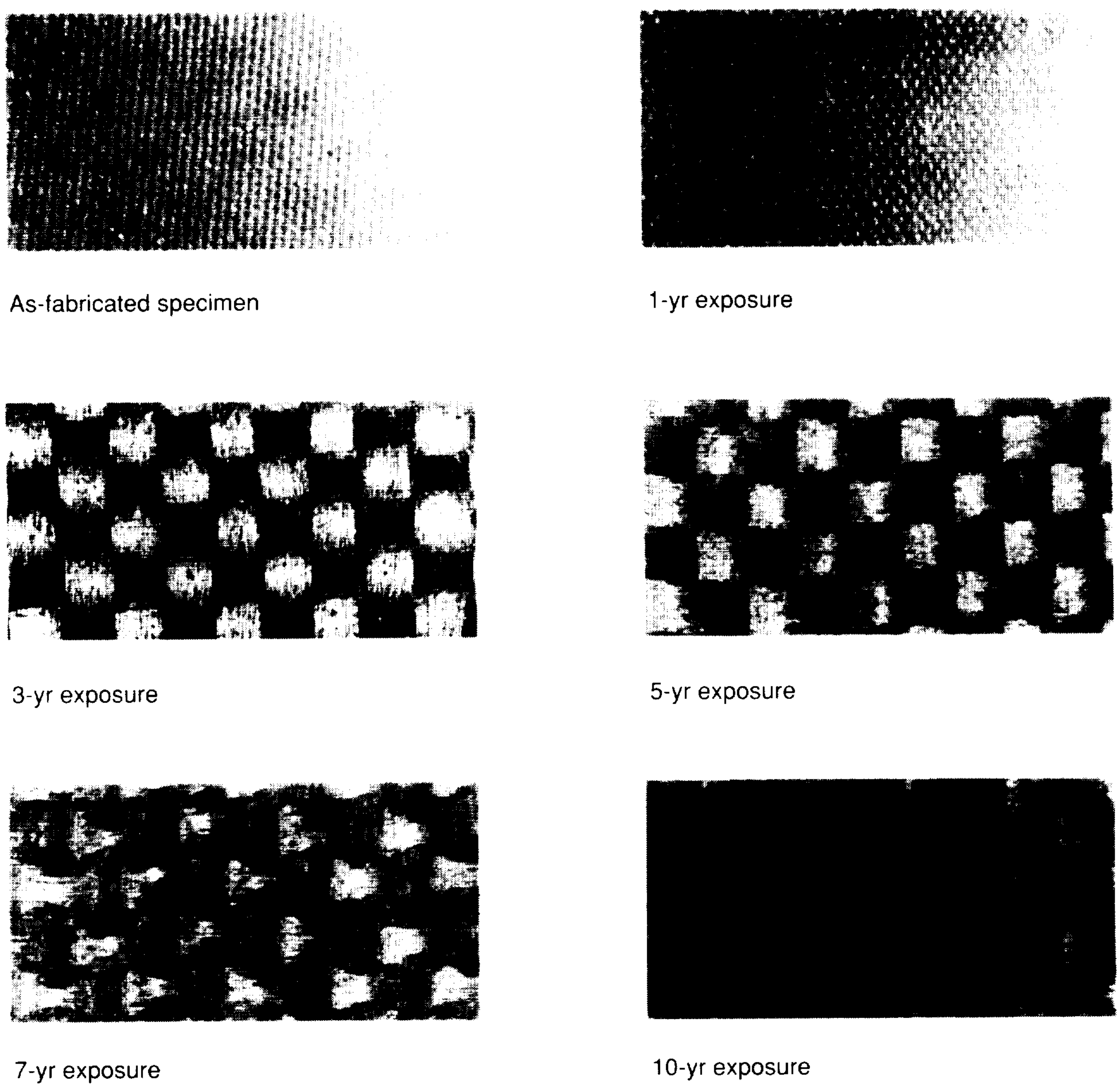
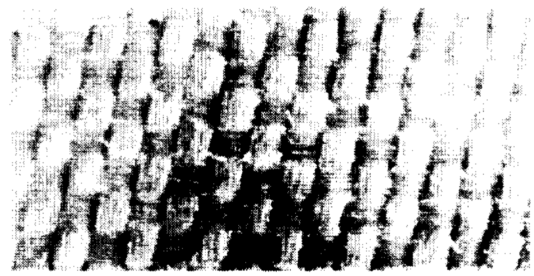
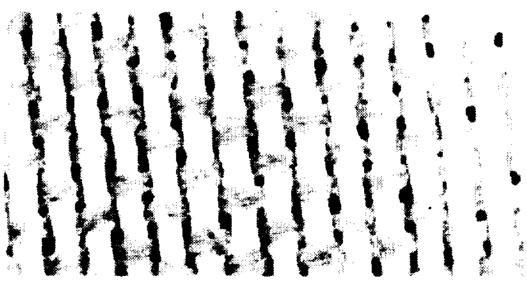


Figure 20. Effects of outdoor exposure on unpainted Kevlar-49/F-185 composite material exposed at Hampton, Virginia (15× magnification).

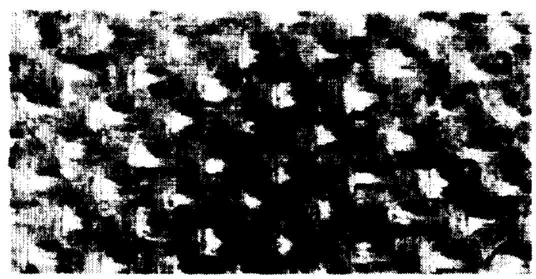
As-fabricated specimen



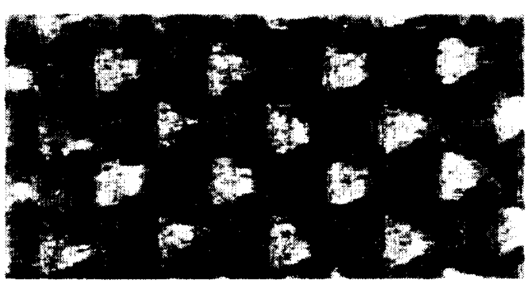
1-yr exposure



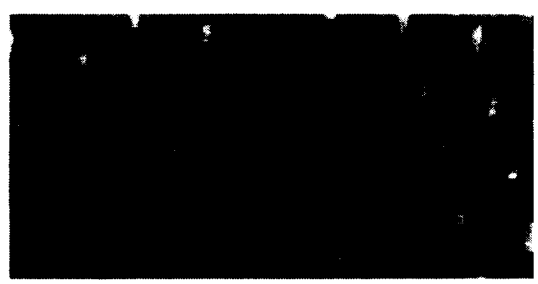
3-yr exposure



5-yr exposure



7-yr exposure



10-yr exposure

Figure 21. Effects of outdoor exposure on unpainted Kevlar-49/LRF-277 composite material exposed at Hampton, Virginia (15× magnification).

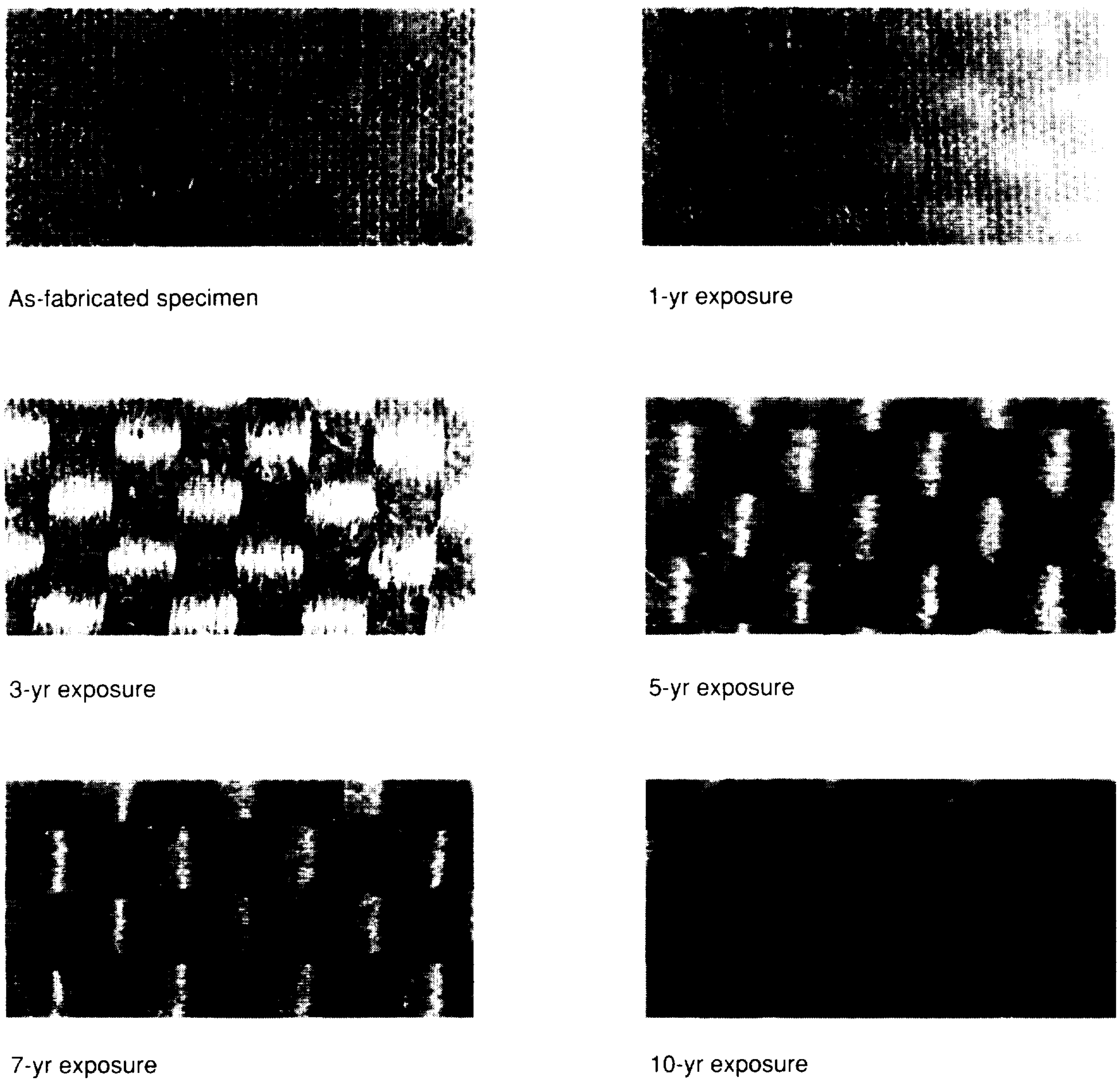


Figure 22. Effects of outdoor exposure on unpainted Kevlar-49/CE-306 composite material exposed at Hampton, Virginia (15× magnification).

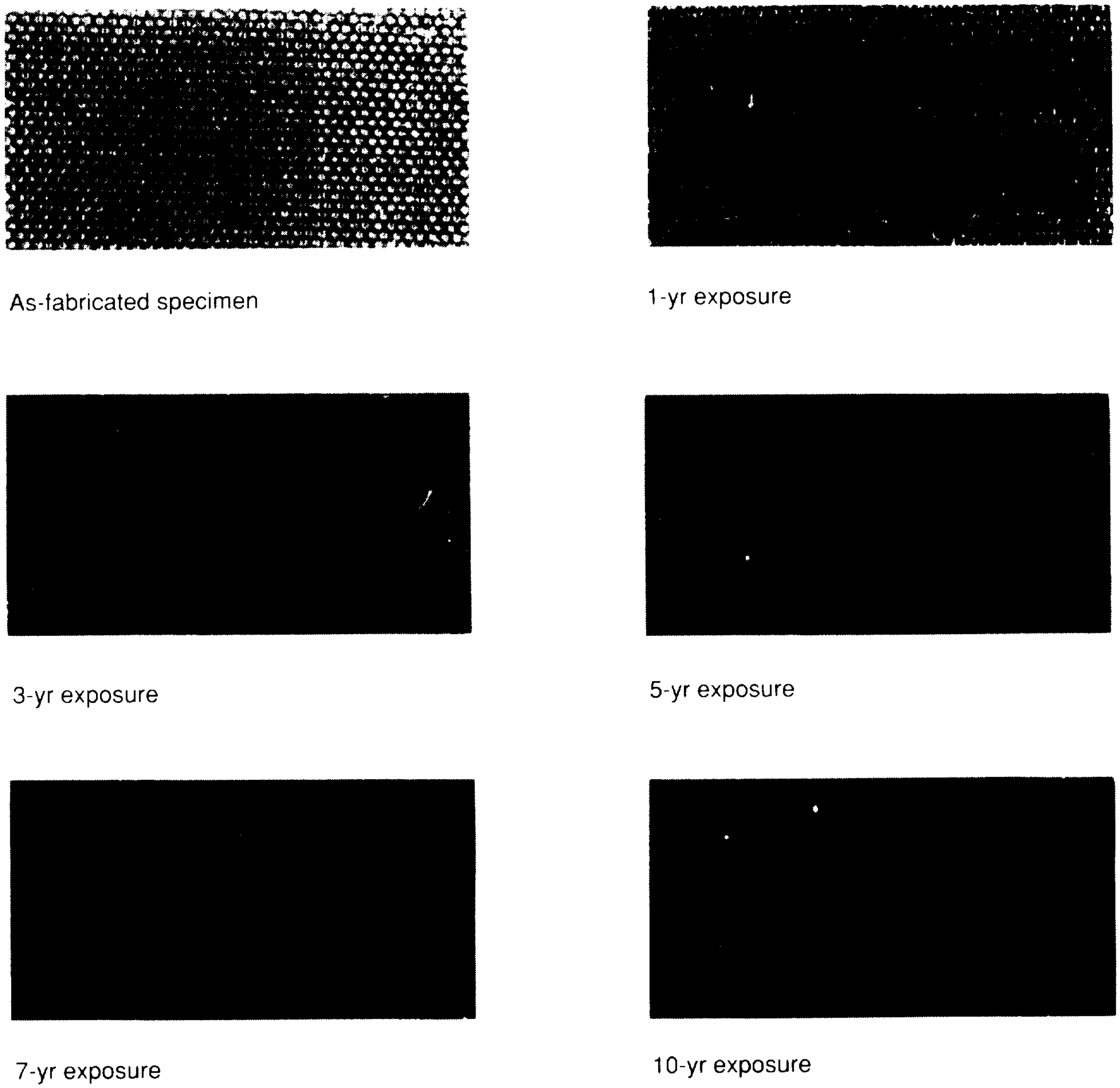
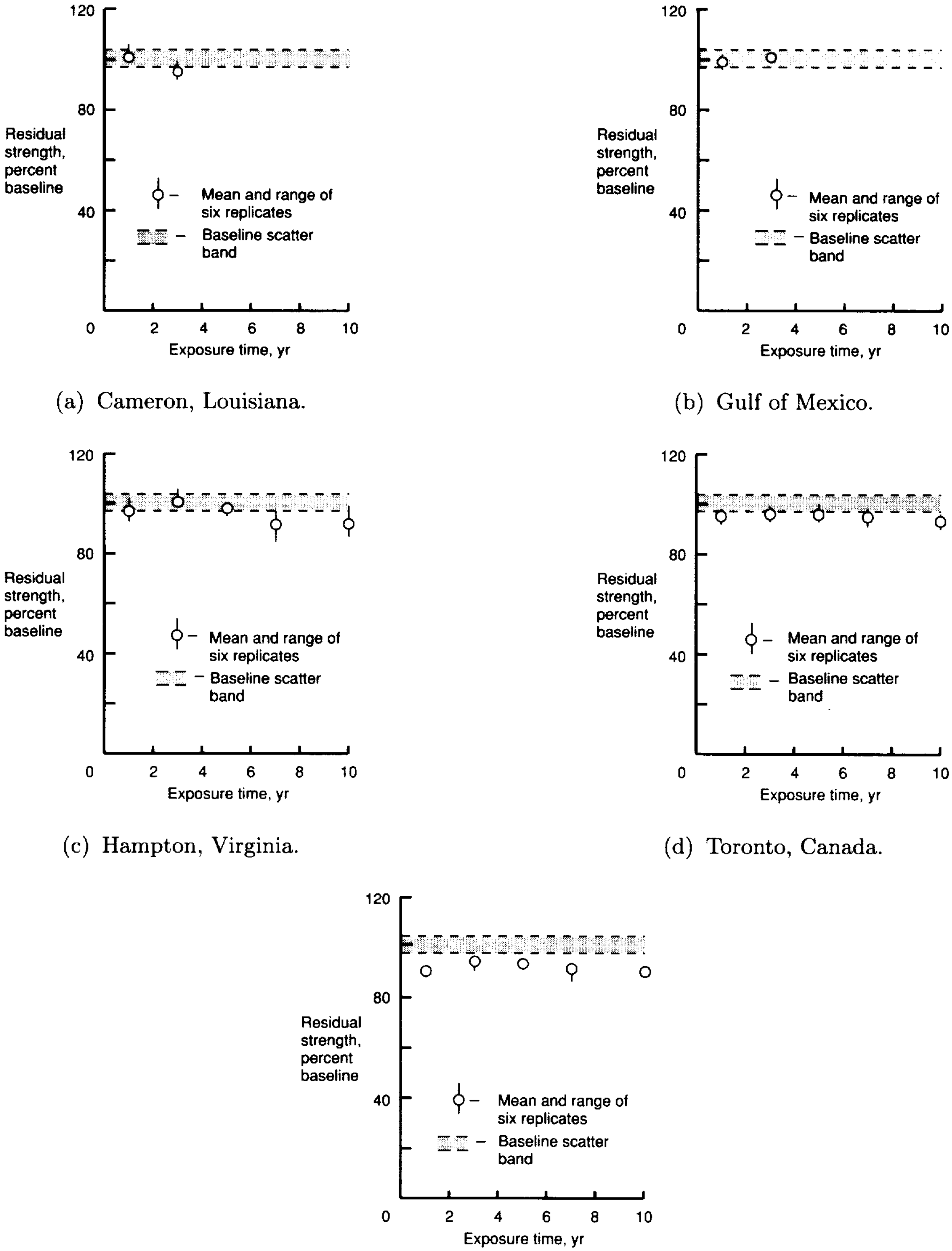


Figure 23. Effects of outdoor exposure on unpainted T-300 graphite/E-788 epoxy composite material exposed at Hampton, Virginia (15× magnification).



(a) Cameron, Louisiana.

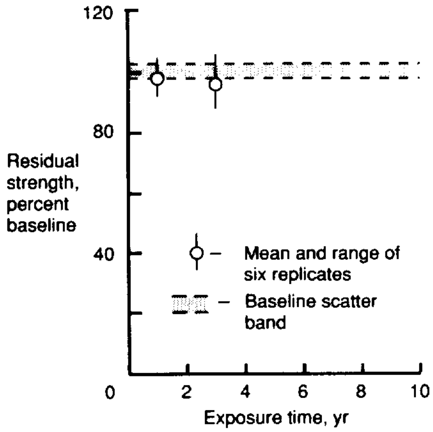
(b) Gulf of Mexico.

(c) Hampton, Virginia.

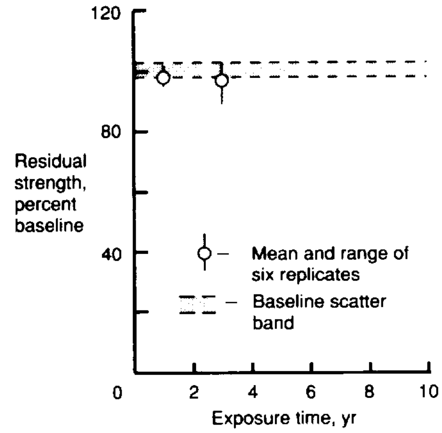
(d) Toronto, Canada.

(e) Ft. Greely, Alaska.

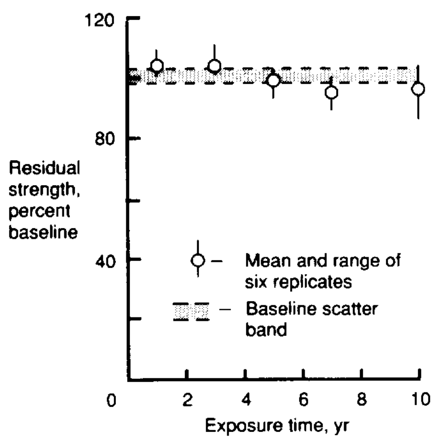
Figure A1. Residual compression strength of Kevlar-49/F-185 epoxy specimens exposed at locations shown.



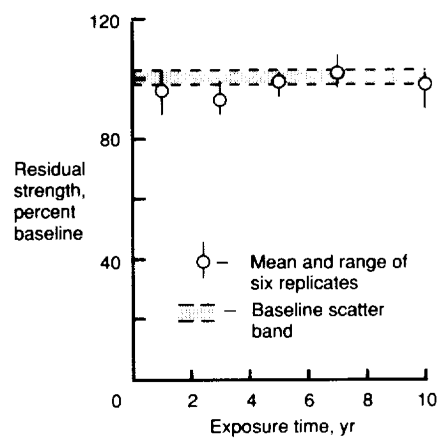
(a) Cameron, Louisiana.



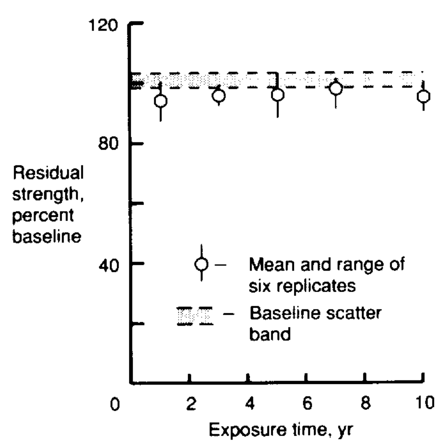
(b) Gulf of Mexico.



(c) Hampton, Virginia.

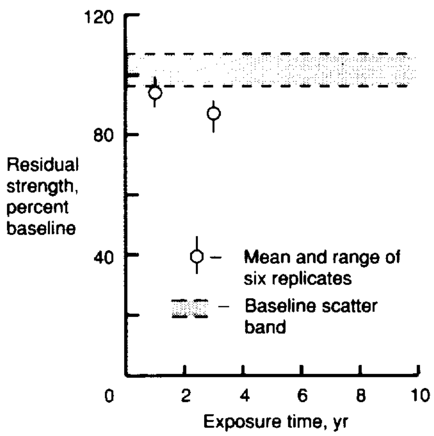


(d) Toronto, Canada.

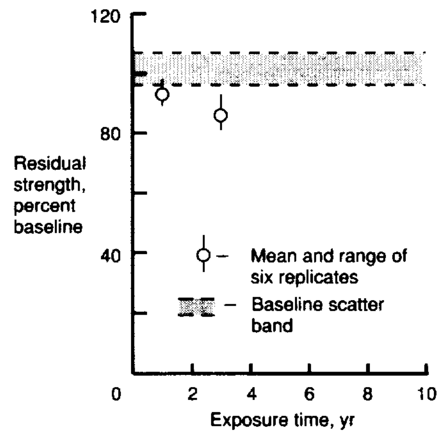


(e) Ft. Greely, Alaska.

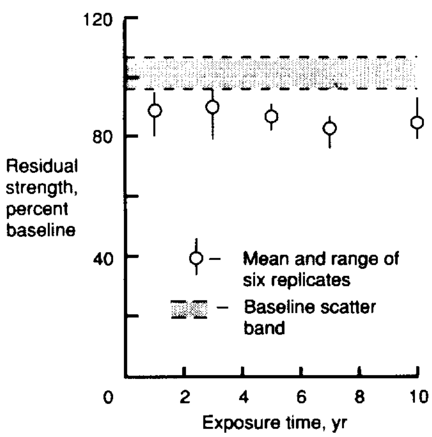
Figure A2. Residual compression strength of Kevlar-49/CE-306 epoxy specimens exposed at locations shown.



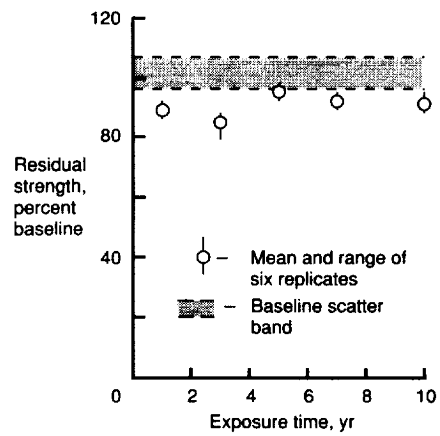
(a) Cameron, Louisiana.



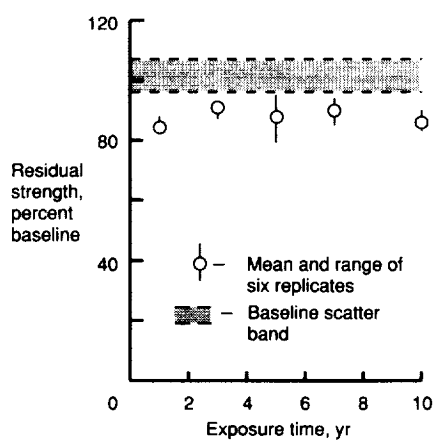
(b) Gulf of Mexico.



(c) Hampton, Virginia.

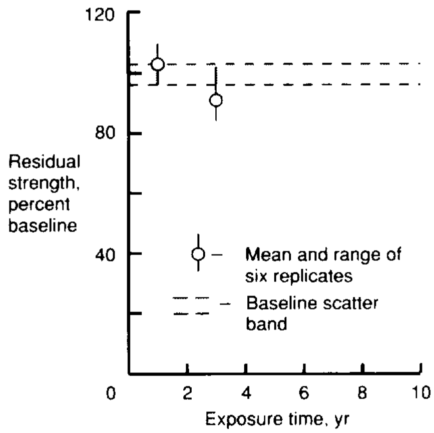


(d) Toronto, Canada.

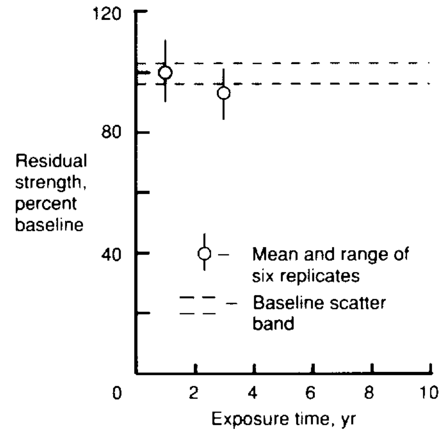


(e) Ft. Greely, Alaska.

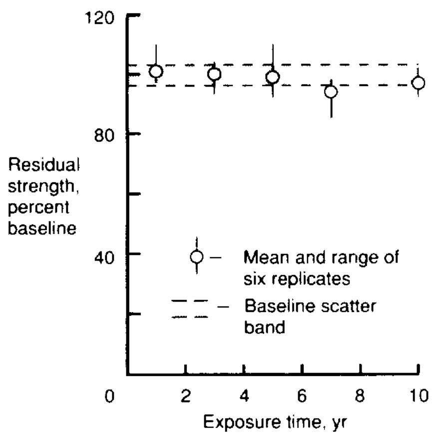
Figure A3. Residual compression strength of Kevlar-49/LRF-277 epoxy specimens exposed at locations shown.



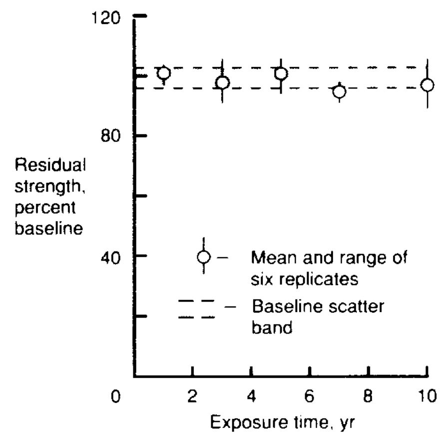
(a) Cameron, Louisiana.



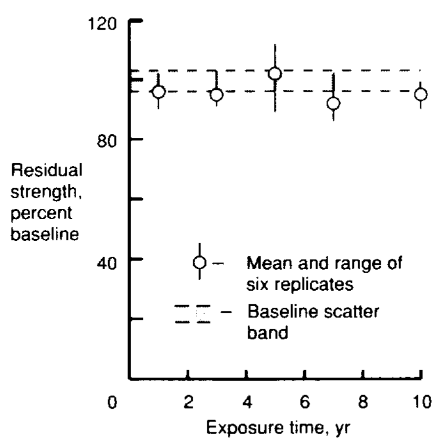
(b) Gulf of Mexico.



(c) Hampton, Virginia.

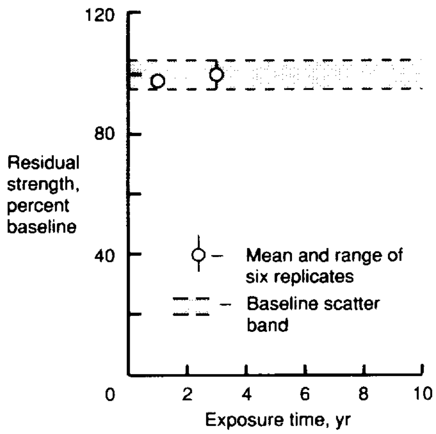


(d) Toronto, Canada.

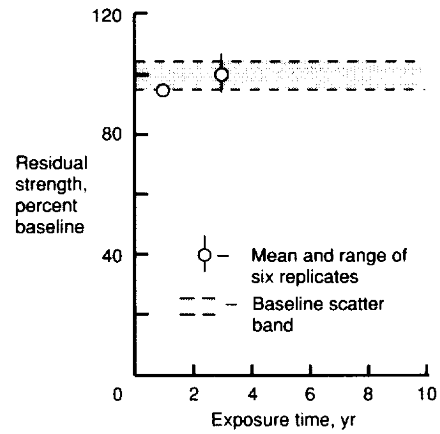


(e) Ft. Greely, Alaska.

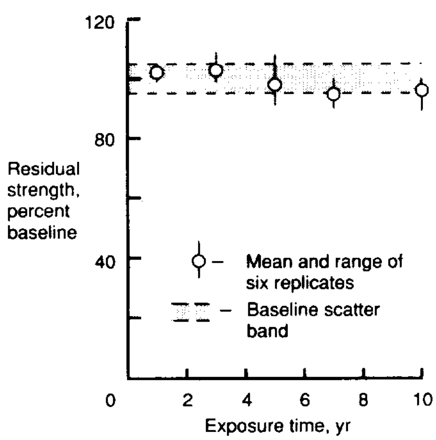
Figure A4. Residual compression strength of T-300 graphite/E-788 epoxy specimens exposed at locations shown.



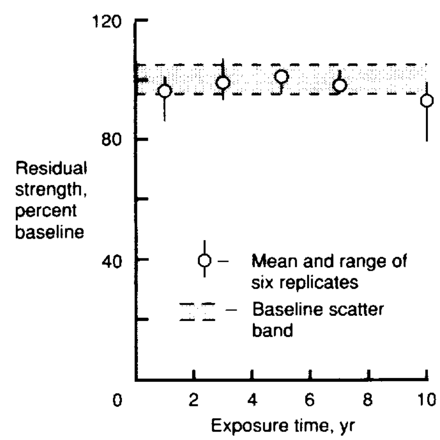
(a) Cameron, Louisiana.



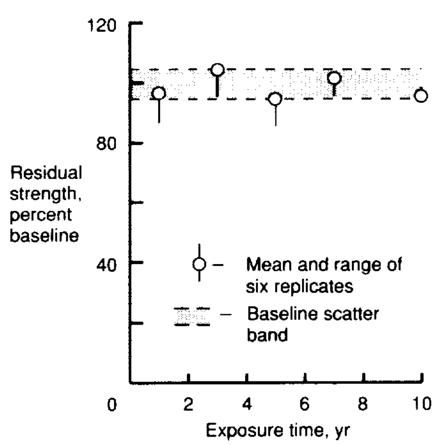
(b) Gulf of Mexico.



(c) Hampton, Virginia.

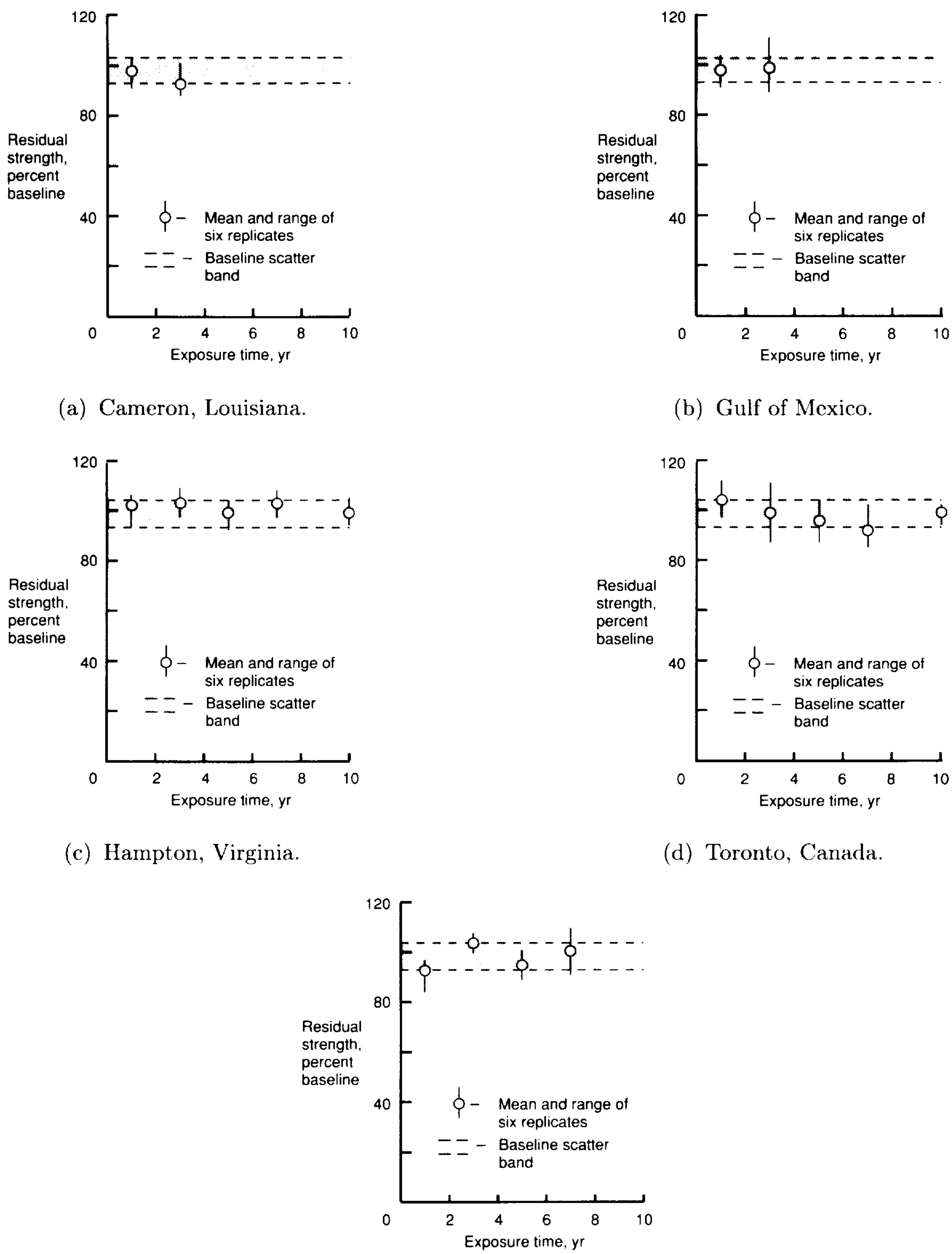


(d) Toronto, Canada.



(e) Ft. Greely, Alaska.

Figure A5. Residual SBS strength of Kevlar-49/F-185 epoxy specimens exposed at locations shown.



(a) Cameron, Louisiana.

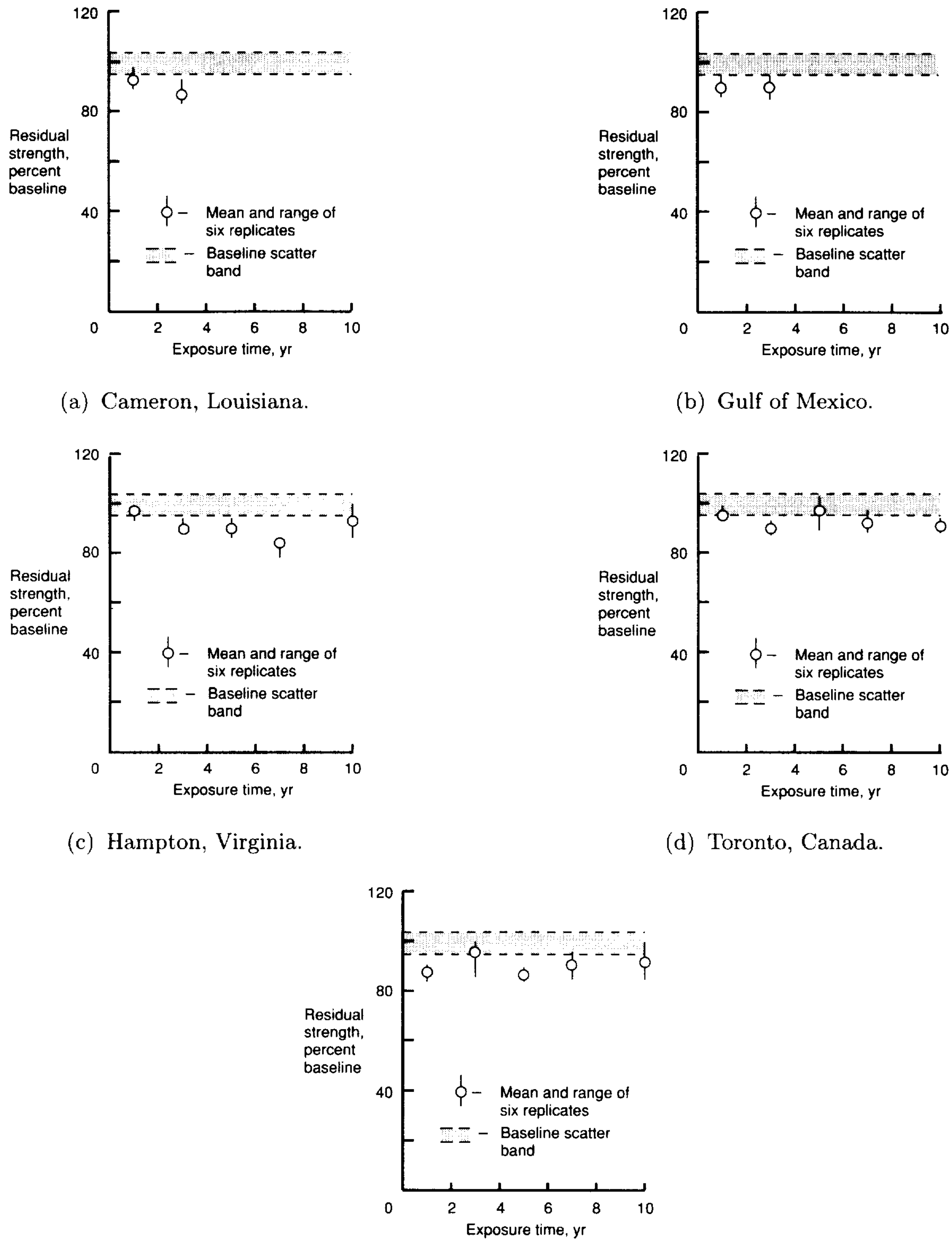
(b) Gulf of Mexico.

(c) Hampton, Virginia.

(d) Toronto, Canada.

(e) Ft. Greely, Alaska.

Figure A6. Residual SBS strength of Kevlar-49/CE-306 epoxy specimens exposed at locations shown.



(a) Cameron, Louisiana.

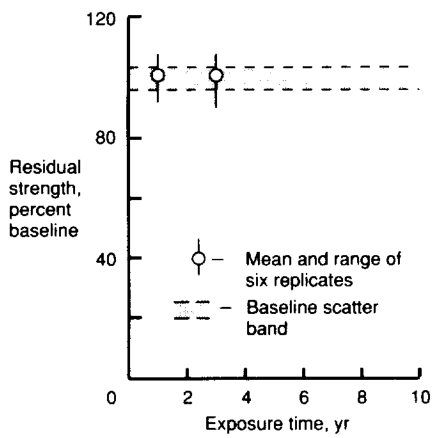
(b) Gulf of Mexico.

(c) Hampton, Virginia.

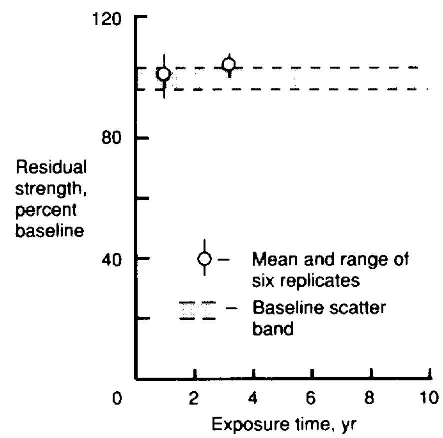
(d) Toronto, Canada.

(e) Ft. Greely, Alaska.

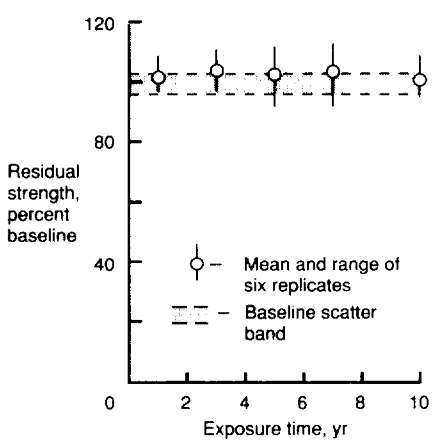
Figure A7. Residual SBS strength of Kevlar-49/LRF-277 epoxy specimens exposed at locations shown.



(a) Cameron, Louisiana.



(b) Gulf of Mexico.



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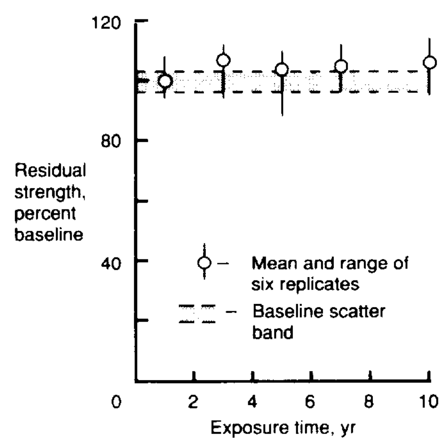

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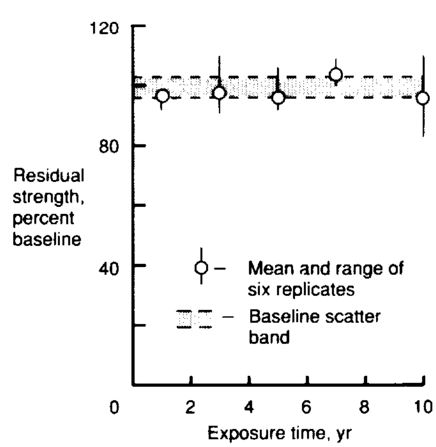
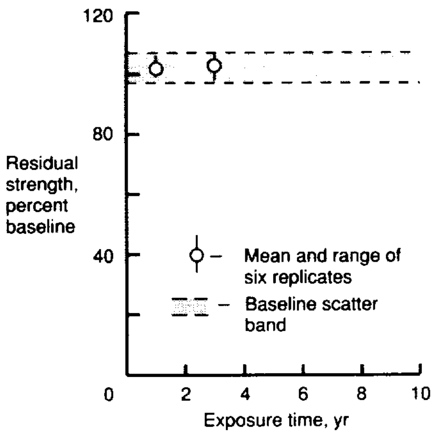
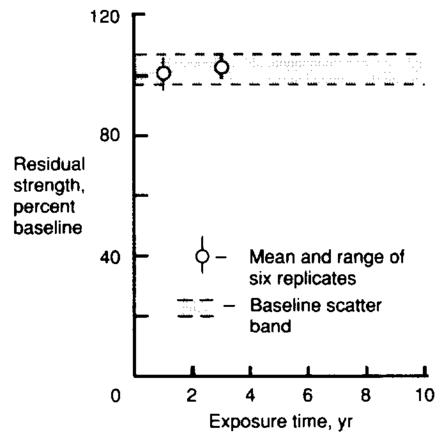


(e) Ft. Greely, Alaska.

Figure A8. Residual SBS strength of T-300 graphite/E-788 epoxy specimens exposed at locations shown.



(a) Cameron, Louisiana.



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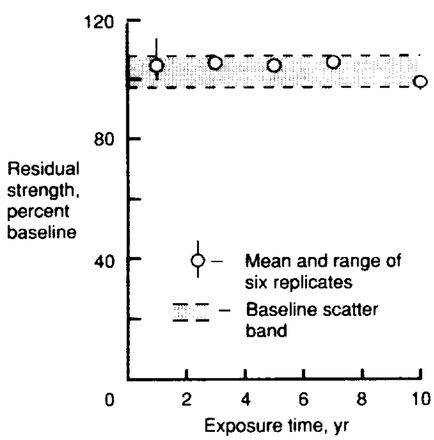
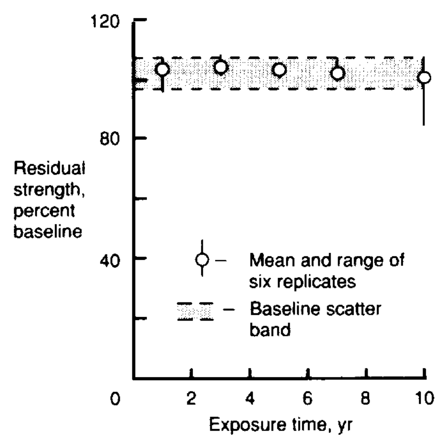
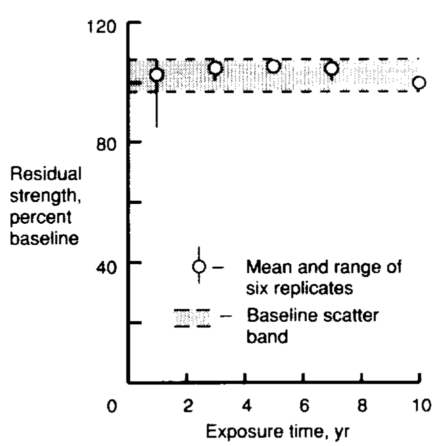


(c) Hampton, Virginia.

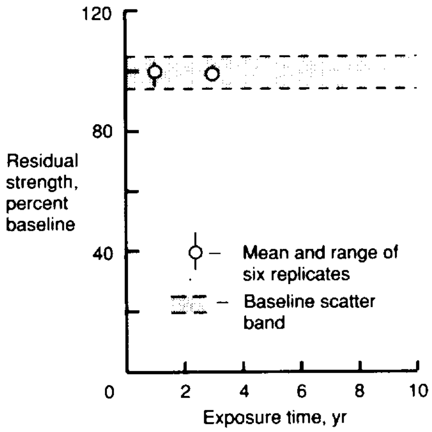


(d) Toronto, Canada.



(e) Ft. Greely, Alaska.

Figure A9. Residual tension strength of Kevlar-49/F-185 epoxy specimens exposed at locations shown.



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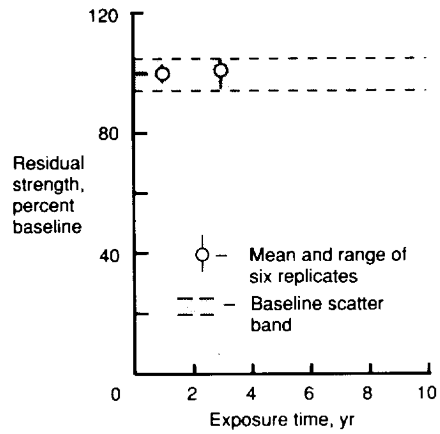
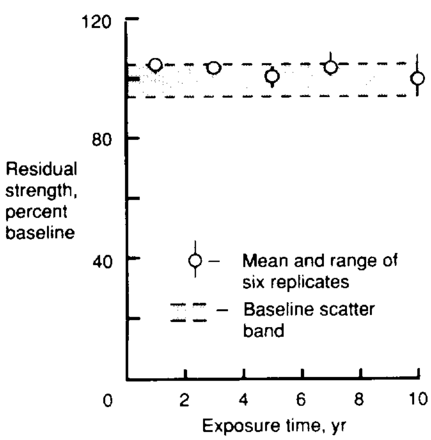


(b) Gulf of Mexico.



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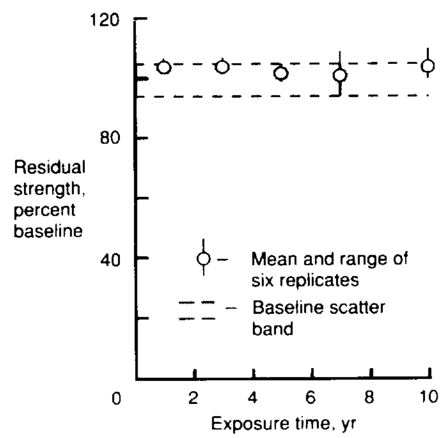
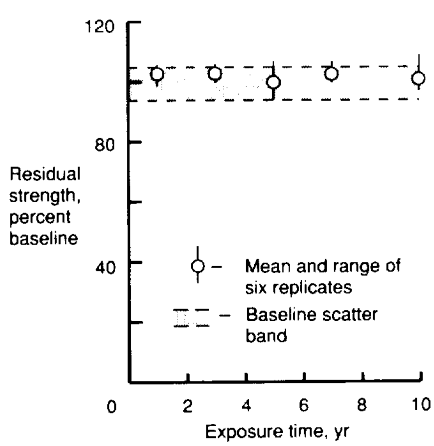
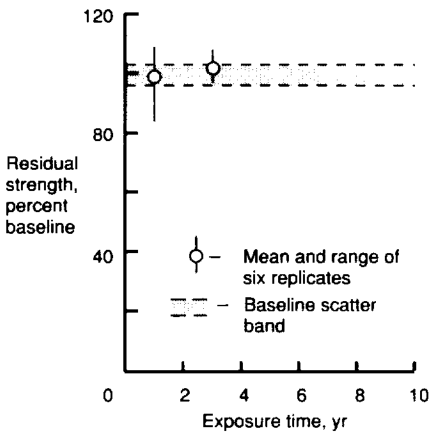


(d) Toronto, Canada.



(e) Ft. Greely, Alaska.

Figure A10. Residual tension strength of Kevlar-49/CE-306 epoxy specimens exposed at locations shown.



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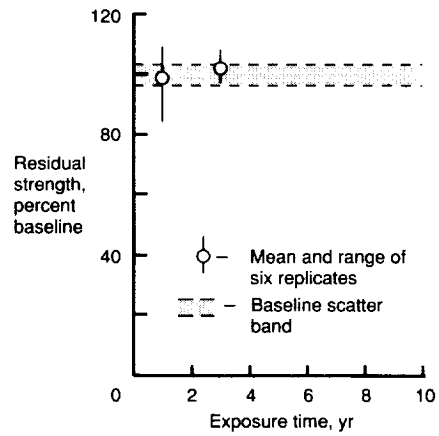
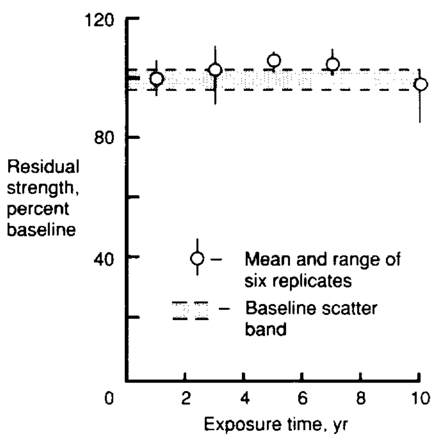
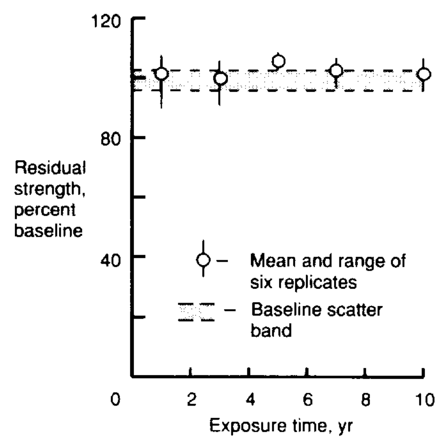


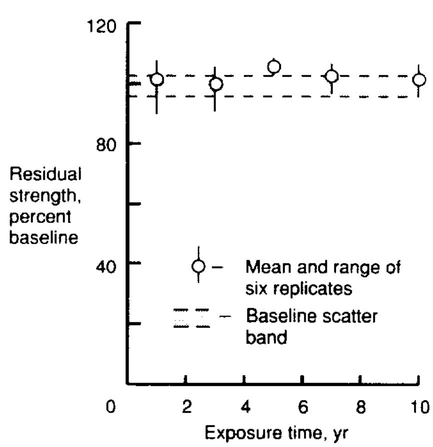
(b) Gulf of Mexico.



(c) Hampton, Virginia.

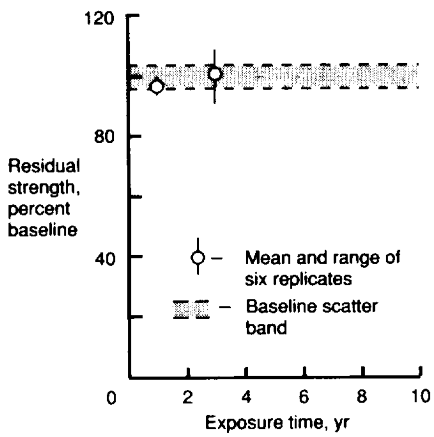


(d) Toronto, Canada.

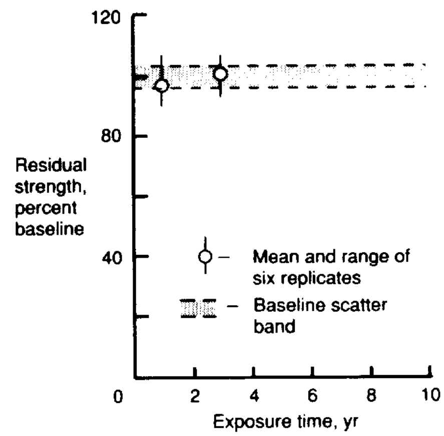


(e) Ft. Greely, Alaska.

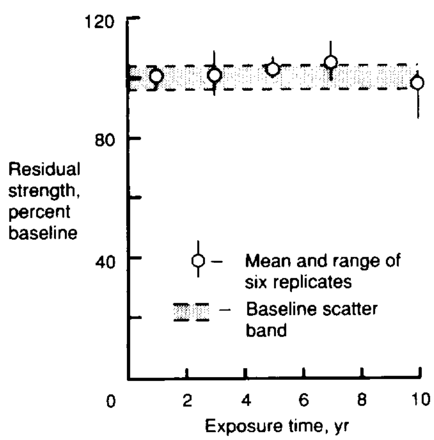
Figure A11. Residual tension strength of Kevlar-49/LRF-277 epoxy specimens exposed at locations shown.



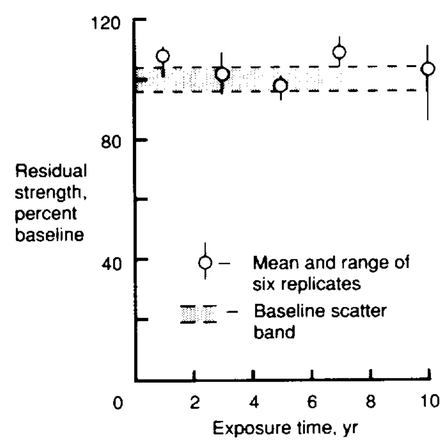
(a) Cameron, Louisiana.



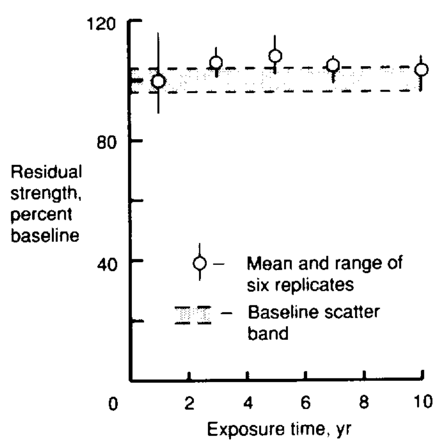
(b) Gulf of Mexico.



(c) Hampton, Virginia.



(d) Toronto, Canada.



(e) Ft. Greely, Alaska.

Figure A12. Residual tension strength of T-300 graphite/E-788 epoxy specimens exposed at locations shown.

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13. ABSTRACT *(Maximum 200 words)*
Residual strength results are presented for four composite material systems that have been exposed for up to 10 years to the environment at five different locations on the North American continent. The exposure locations are near where the Bell Model 206L helicopters, which participated in a flight service program sponsored by NASA Langley Research Center and the U.S. Army, were flying in daily commercial service. The composite material systems are (1) Kevlar-49 fabric/F-185 epoxy; (2) Kevlar-49 fabric/LRF-277 epoxy; (3) Kevlar-49 fabric/CE-306 epoxy; and (4) T-300 graphite/E-788 epoxy. Six replicates of each material were removed and tested after 1, 3, 5, 7, and 10 years of exposure. The average baseline strength was determined from testing six as-fabricated specimens. More than 1700 specimens have been tested. All specimens that were tested to determine their strength were painted with a polyurethane paint. Each set of specimens also included an unpainted panel for observing the weathering effects on the composite materials. A statistically based procedure has been used to determine the strength value above which at least 90 percent of the population is expected to fall with a 95-percent confidence level. The computed compression strengths are 80 to 89 percent of the baseline (no-exposure) strengths. The resulting compression strengths are approximately 8 percent below the population mean strengths. The computed short-beam-shear strengths are 83 to 92 percent of the baseline (no-exposure) strengths. The computed tension strength of all materials is 93 to 97 percent of the baseline (no-exposure) strengths.

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