NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

**SAFTEY ENHANCEMENT OF COMPOSITES
VIA PERIODIC
PROOF TESTING**

by

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September, 1993

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE 1993,September.	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE SAFETY ENHANCEMENT OF COMPOSITES VIA PERIODIC PROOF TESTING

5. FUNDING NUMBERS

6. AUTHOR(S) Joseph H. Woodward

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE
*A

13.

ABSTRACT *(maximum 200 words)*

The development of new composite materials, which lack the historical field data base, has led to the need for an accelerated life testing method applicabl. to composites. Accelerated life testing by increasing the sustained stress levels requires the modeling and validation of a strength-life relation. Proof testing of composite fibers by over-loading is one step in the understanding of the relationship. It is also important in the reliability and safety assurance in deployment of composite structures.

A parametric study examined the strength-life relation of composite fibers and a methodology to analyze the fiber failures after proof testing. The fiber statistical strength was modeled by a probability of failure model while a deterministic approach was taken considering individual fibers and the associated life reduction each fiber experienced during the proof testing procedure. Also studied was the distribution of the first failure to occur after proof testing in order to understand the effects of the sustained load and the proof load on fiber life.

14. SUBJECT TERMS Composite Fiber Reduced life Fractional Life Distribution.

15. NUMBER OF PAGES * 74

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Safety Enhancement of Composites
Via Periodic
Proof Testing

by

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September, 1993

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ACKNOWLEDGEMENT

Many thanks go to my family for their support and encouragement. I would especially like to thank my advisor, Professor Ed Wu, for his guidance and the dedication he provided. I truly appreciate the education I received from him.

I. INTRODUCTION

Aircraft structures built of composites materials are becoming the norm rather than the exception today. As stronger fibers are developed in conjunction with new matrix materials, the advantage of higher strength to weight and stiffness to weight ratios become more apparent. The dynamic development of composites necessitates a predictive methodology for safety and reliability in the absence of historical data. A designer using a homogeneous material such as steel or aluminum only has the option to vary geometry in order to meet the required loading on the structure. Using a composite material, not only can the geometry be varied, but the material itself becomes a part of the design process. The design of composites must include a parametric understanding of the strength to life durability relation. Unfortunately, the historical data regarding safety and reliability is not available for newly developed composites.

Mathematical modeling of the strength life relation must be based on the failure process of the specific material. The failure process for composites is inhomogeneous, typified by local fiber failures at isolated sites. The load sharing ability of the matrix binder will temporarily delay catastrophic failure of the composite. As the stress or time increases, the number of failure sites increases and chance clustering of such sites ultimately leads to failure. Experience in composite strength modeling has demonstrated that given the fiber strength statistics, the probability of failure of the composite can be predicted. Since the fiber failure process is homogeneous, the modeling of inhomogeneous composite life will be based on the fiber statistics.

Currently being conducted at the Naval Postgraduate School's Advanced Composites Laboratory is a strength-life experiment involving two sets of statistically identical AS-4 graphite fibers. The life statistics of the fibers, which have been subjected to a sustained tensile load, are being collected and analyzed. Concurrent with the life testing, a proof test was conducted on two subsets of the fibers in order to validate the strength life model and to allow for accelerated life testing.

The focus of this study is the life sensitivity to parameter variation and the post-proof test minimum time to failure life distribution.

II. BACKGROUND

A. APPLICATION TO MISSION

1. Structural Safety

Structural safety may be considered as the number of failures which occur during a given time period. For example, the failure of a composites helicopter blade may be modeled by an appropriate probability density function (pdf) as shown in Figure 1.

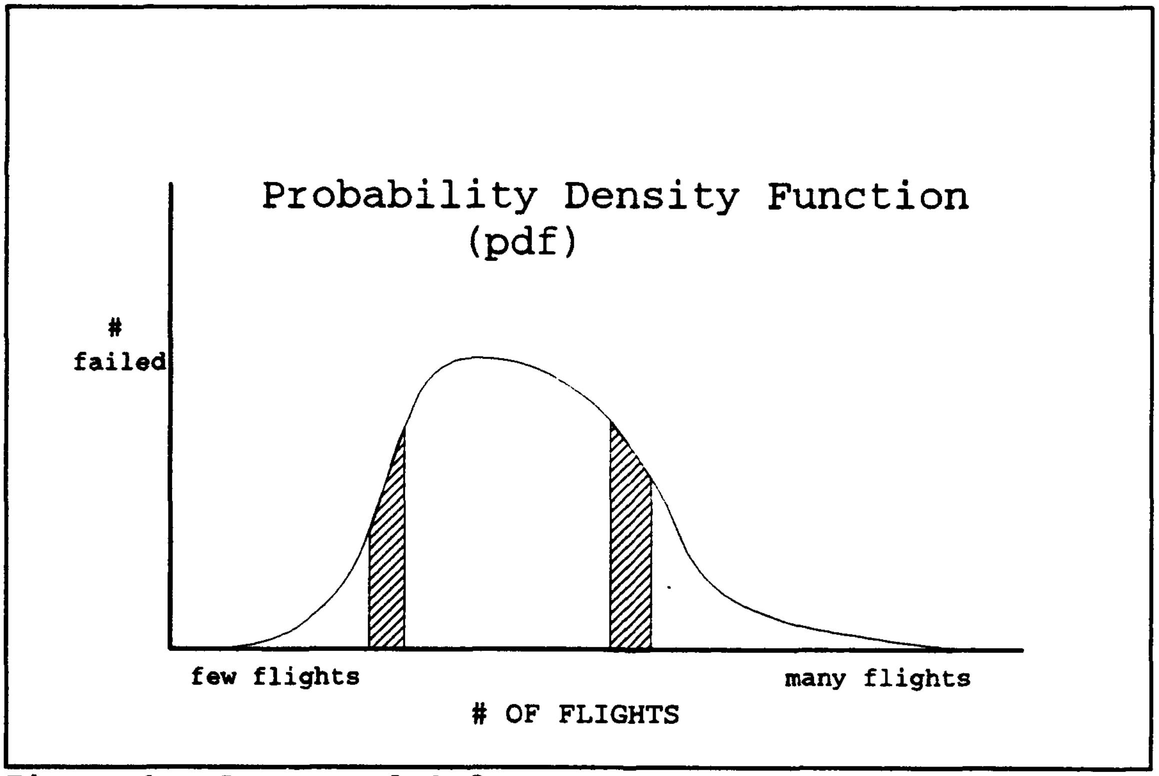

Figure 1. Structural Safety

The risk associated with a specific blade is then the probability that a blade which has lasted a certain number of flights, may fail during its subsequent flight. Therefore the height of the curve is a measure of safety. A low height means a safer blade and conversely, a high region indicates a relatively unsafe blade.

The time period used to define the safety of a blade is one flight or a block time, but no two flights produce the same stress history on a blade. Therefore the block time must be convoluted to a reduced time at an equivalent stress. The idea of a reduced time was introduced by Coleman [Ref. 1] as

$$\tau(\cdot)=\frac{1}{\hat{t}}\int_{t_0}^{t_f}K(S(\xi))\,d\xi$$

That is, given a time dependent stress history, $S(\zeta)$, and the physical breakdown process, K, the fractional life of the fiber used between t_0 and t_f is τ, where $\hat{t}$ is an intrinsic normalizing time parameter. An example of reduced time for a stress history is given in Appendix A.

2. Availability

While the probability density function (pdf) is useful in estimating safety, it can only provide guidance to

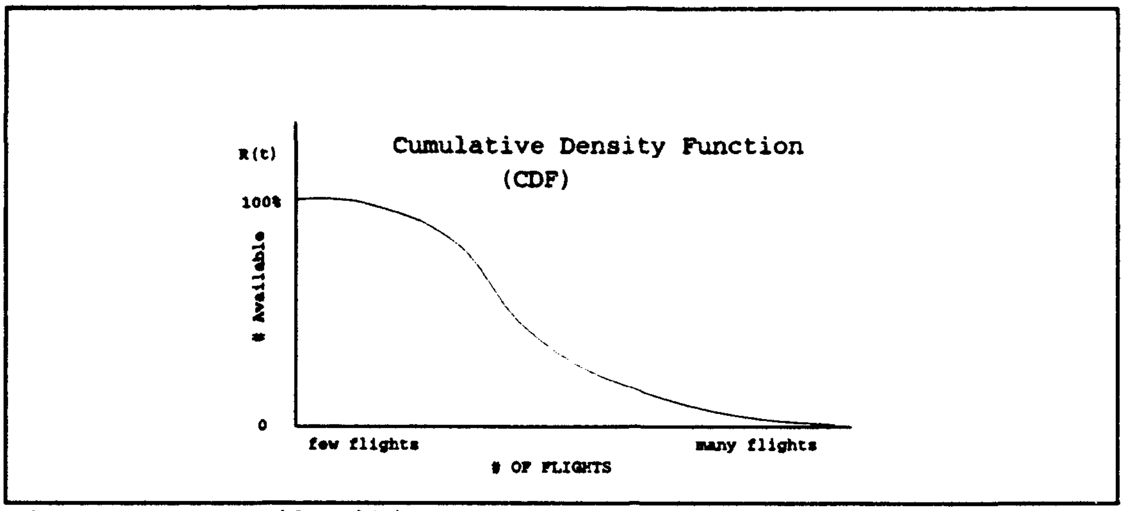

Figure 2. Availability

logistics and planning associated with the availability of a fleet of aircraft. If the pdf for the set of helicopter blades is known, then the cumulative density function (CDF) may be found by integrating the pdf [Ref. 2]. The CDF in this example is then the total number of blades, F(t), out of the original set that have failed up to a given time. Also, 1-F(t) is the number of blades available, R(t), at any time (see Figure 2). Early on there are many blades available but as the blades near the end of their planned service life, the inventory has dropped. The availability curve may then be used as an acquisition planning tool in order to optimize purchases of new equipment.

3. Feasibility

Another utility of the pdf can be found in estimating the success of a mission, or a measure of the feasibility. The instantaneous failure rate of the blades, $\lambda(t)$, may be dividing the pdf (# of failed) by R(t) (# available) as shown in Figure 3. The success rate, SR(t), can then be defined a 1-λ(t). The success rate may be used in conjunction with the availability curve in order to determine mission feasibility. For example, a certain mission that requires 100 aircraft would need 100/SR(t) aircraft to be deployed in order to ensure mission accomplishment. Looking at the number of aircraft available at that time would tell if the mission were possible. As the failure rate increased, there would come a point where the number of aircraft required would exceed the number available. By knowing the pdf, one could then predict not only the safety associated with a structure, but when a replacement must be brought on-line.

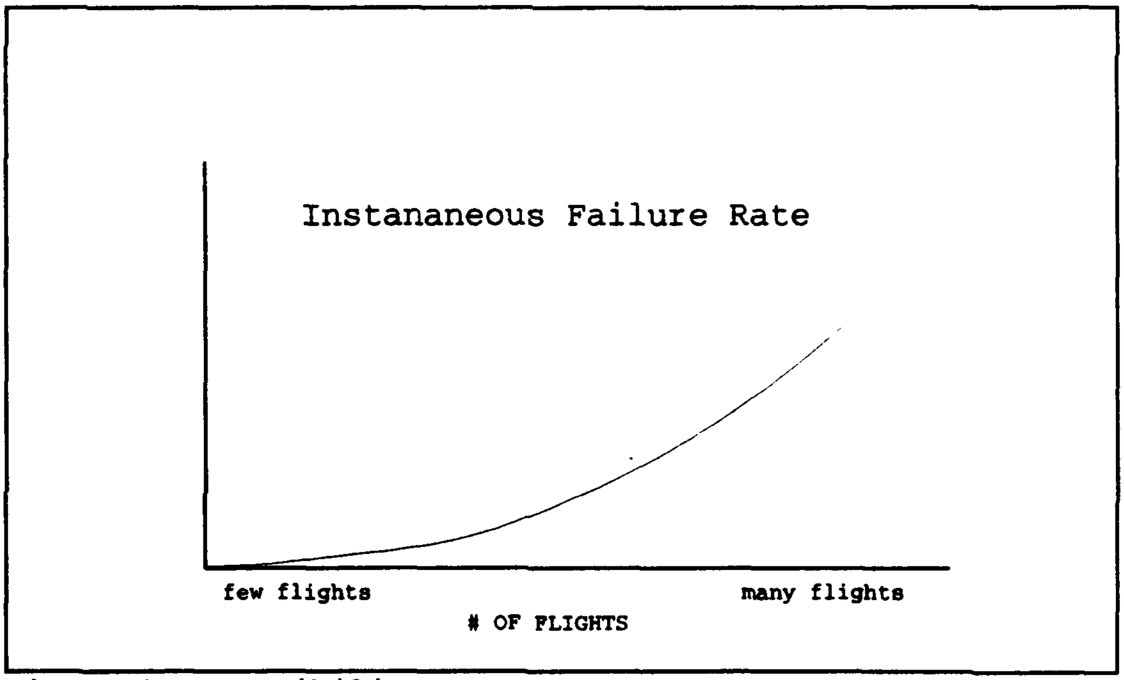

Figure 3. Feasibility

B. BASIS FOR PROOF TESTING

1. Homogeneous Brittle Material

Given that a material's durability (life under a stress history) inherently contains statistical variability, there always exists a finite probability of failure. The probability of failure depends on the location of the time period with respect to the mean age. The underlying idea of proof test is to overload each sample so that the weak samples will be failed during the overload and therefore eliminated in the subsequent deployment. This assumes that the samples which survived the proof testing are not significantly damaged by the overload (in strength) and therefore its effect on the life of the sample is minimal. A rational proof test methodology must be able to quantitatively characterize the damage during proof test. Such methodology cannot be empirical because one sample cannot be tested in strength and then in life. An understanding of the failure mechanism is needed.

For a homogeneous brittle material, the failure mechanism is flaw growth. Given a specimen with a crack of length a, the strength of that specimen can be related to the crack length by classical fracture mechanics as

$$k=\sigma^2\sqrt{a}$$

where k is the stress intensity factor. A specimen with a short crack is stronger than a specimen with a longer crack for the same stress intensity factor (see Figure 4). At any time, the length of the crack may be determined by

$$a=\int_{t_0}^{t_f}\left(\frac{\partial a}{\partial \xi}\right) d\xi$$

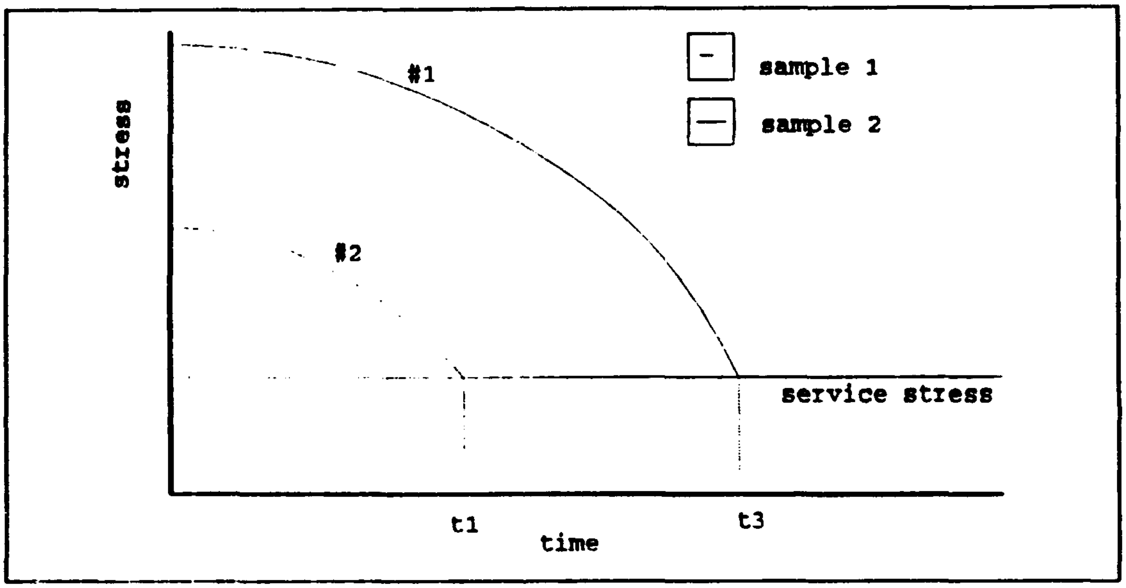

Figure 4. Homogeneous Crack Growth

where $\delta a/\delta \xi$ is the rate of crack growth. But the rate of crack growth is itself a function of the applied stress σ, i.e., $\delta a/\delta \xi = a(\sigma)$.

Considering two specimens as shown in Figure 5, it is desired to apply an intermediate proof load at t_0 which would cause the weaker sample to fail but not the stronger. By failing the weaker specimen in a controlled environment, it is removed from service and prevented from failing while in

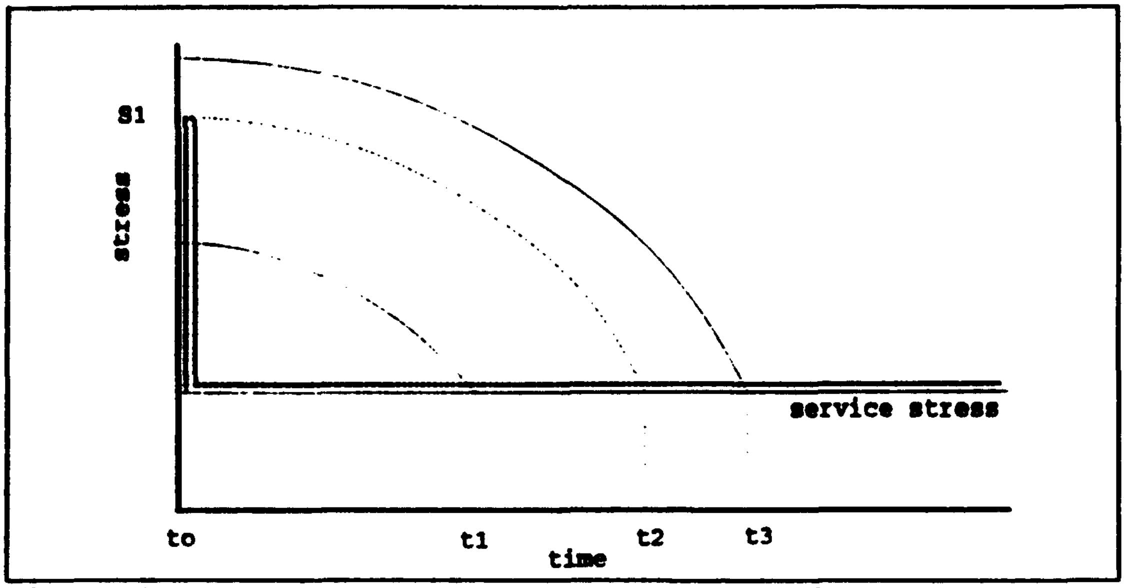

Figure 5. Proof Test of Homogeneous Material

operational use. If the breakdown function is known, the absolute safety up to time t_2 may then be guaranteed.

If the crack growth rate for each sample is the same and the stress level is identical, i.e., $a(\sigma)_1 = a(\sigma)_2$, it implies a homologous relationship between the samples. Under the condition of homologous, the effect of proof testing may be examined in a deterministic setting. Physically this implies that each sample with an intrinsic (but different) strength will have a strength degradation contour as depicted in Figure 5. Given this hypothesis, a high proof load at an early time t_0 will assure safety up to time t_2. This proof test strategy has two deficiencies. One, the high proof load will eliminate a larger number of samples, which may otherwise provide some useful service between t_0 and t_2; a deficiency of economics. Two, the homologous condition may not hold for an extended time period; thus, the safety up to t_2 is <u>not</u> guaranteed; a deficiency in efficiency.

The proof test methodology may be modified to include several strategically placed proof loads of smaller magnitudes dispersed through out the service life of the structure (Figure 6.) This method would involve a shorter time extrapolation, allowing for piece-wise homology and some useful service would be obtained by samples that otherwise would have been failed by one large proof load.

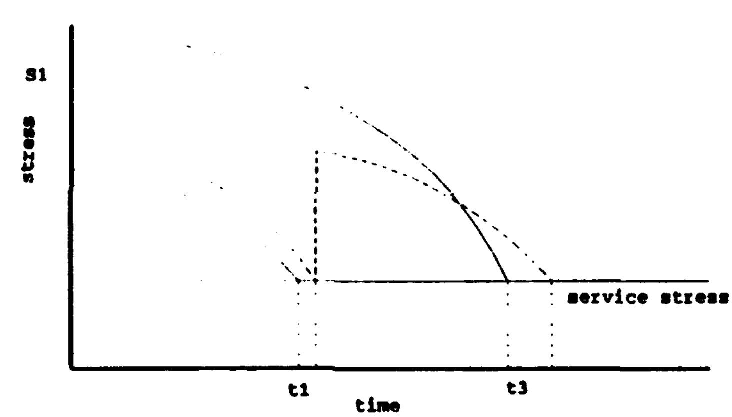

Figure 6. Multiple Proof Tests

2. Heterogeneous Material

The failure mechanism for a composite structure is not homogeneous. Rosen [Ref. 3] has modeled the load transfer between fiber bundles and matrix by the Local Load Sharing model. The fibers carry the stress applied to the structure while the matrix transfers the load to adjacent fibers. When a fiber fails, the longitudinal stress at the break drops to zero while the shear stress reaches a maximum as characterized in Figure 7. At the fiber break there is a region known as

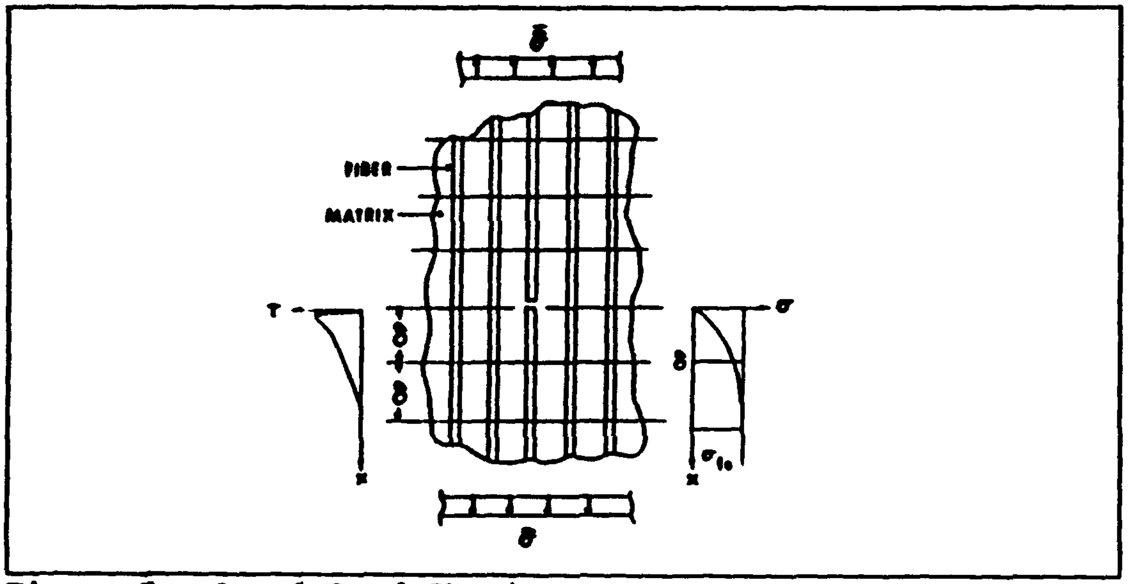

Figure 7. Local Load Sharing

the ineffective length, δ, over which the fiber does not carry any longitudinal stress. The ineffective length is given by

$$\delta = \left(\left(V_f^{-\frac{1}{2}} - 1 \right) \frac{E_f}{G_m} \right)^{\frac{1}{2}} \cosh^{-1}\left(\frac{1 + (1+\phi)^2}{2(1-\phi)} \right) d_f$$

where: V_f is the volume fraction of the fiber
E_f is the modulus of the fiber
G_m is the shear modulus of the matrix
ϕ is the fractional value, called the fiber load sharing efficiency, below which the fiber is considered not effective.

If enough fibers fail in close proximity to each other, this clustering of failures can lead to catastrophic failure of the composite.

The composite strength can be modeled by knowing the fiber strength, matrix ability to transfer load and the fiber/matrix interface. Harlow and Phoenix [Ref. 4 and 5] have developed a model which predicts the probability of failure of a composite in tension based on fiber strength statistics and ineffective length. The model has been extended by Harlow and Wu [Ref. 6] to include multi-modal fiber failure model, which has been verified by Wu [Ref. 7], Storch [Ref. 8], Kunkle [Ref. 9], Englebert [Ref. 10] and Johnson [Ref. 11].

In the case of a composite helicopter blade, a proof load applied directly will lead to unnecessary failure of fibers because of the load sharing. Any over load would lead to clustering of failure sites in the structure as the stress on surrounding fibers increased. By removing or reducing the load transferring ability of the matrix during proof test, the clustering would be avoided. A possible method to reduced the influence of the matrix would be by heating the composite structure (Wu [Ref. 12]).

3. Composite Fiber

B. Coleman's failure potential theory is based on the "weakest link" idea and is a stochastic function between fiber strength and fiber life [Ref. 1]. If an individual fiber is considered, the fiber has either failed or remains intact, and the failure is described by a binomial distribution. For a fiber material with a high modulus, the failure mechanism is flaw growth. If the flaw is greater or equal to a_{crit} the fiber fails, and if the flaw is less than a_{crit}, the fiber will survive. As the diameter of the fiber becomes smaller, so does the allowable flaw size. If the fiber is divided into many equal volumes, referred to as the metric, and the flaw density within each metric is low, the binomial distribution becomes Poisson. The probability of failure at $t=t_1$, given a stress σ, is $F(t=t_1|\sigma) = 1-\exp(-\Psi(\tau))$. Because the failure of the fiber is homogeneous to mechanism (flaw growth) the hazard $\Psi(\tau)$ is of the Weibull form. That is, $\Psi(\tau) = \tau^a$, where τ is the reduced time as stated earlier.

III. EXPERIMENTAL PROOF TEST PROGRAM

Based on the background summarized, an experimental program is designed to collect graphite filament life data under sustained constant loads. The purpose of the experimental program is three fold. One is to characterize, by actual data, a formulation of the breakdown rule K. For example, if K is of the power law form, what are the values for t and ρ. Two, to examine the validity and range of the strength-life homologous correspondence. And three, to explore the effect on life of the proof test overload.

A total of 512 test stations for filament life testing have been designed and constructed. These stations can apply a sustained load to a single filament fiber sample using dead weights with provision to isolate external disturbances such as those caused by earthquakes. Fiber filaments from two spools of graphite fibers (AS-4 manufactured by Hercules Corporation) have been put on sustained load, Ref. 12. These two spools were selected because they have different statistical characteristics in strength, as noted by Englebert [Ref.10]. Allocation of the test stations are equally divided into 256 stations for each of the two spools. Each of the 256 stations are further subdivided into three load levels as indicated in Figure 8. Some of the fibers at the highest load have been realized in life while most of the samples at the

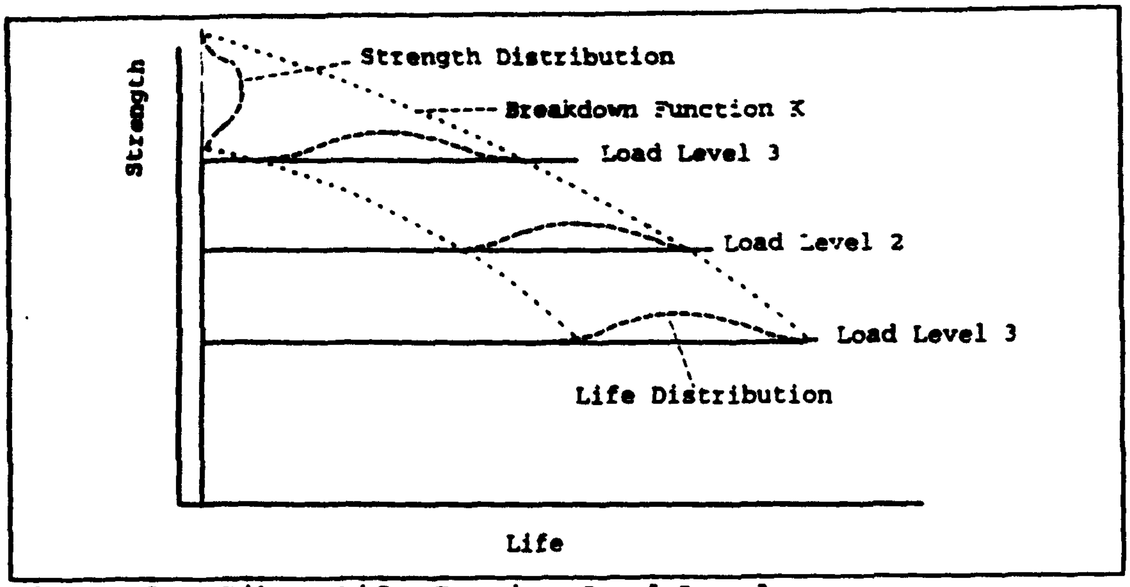

Figure 8. Fiber Life Testing Load Levels

lower load levels are still surviving. In time, with an adequate number of failures as depicted by the data band, the parameters for the breakdown rule K can be assessed. Simultaneously, the two spools with different strength characteristics may produce two different data bands as depicted in Figure 9. Comparison of these two data bands by appropriate probability based statistical methods can confirm or reject the homologous damage hypothesis, i.e., longer life is associated with higher strength.

Finally, in this investigation, proof test by overload is performed on half of the surviving samples under the highest sustained load level. The subsequent life of the samples surviving the proof load can then be compared to those samples that were not subjected to the proof test as illustrated in Figure 10.

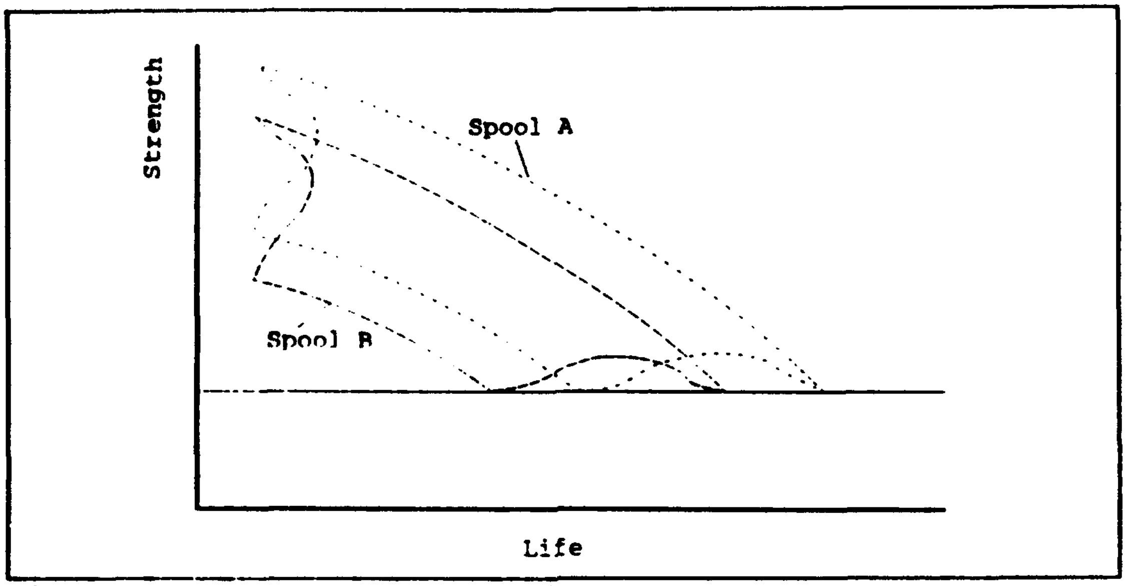

Figure 9. Strength Degradation

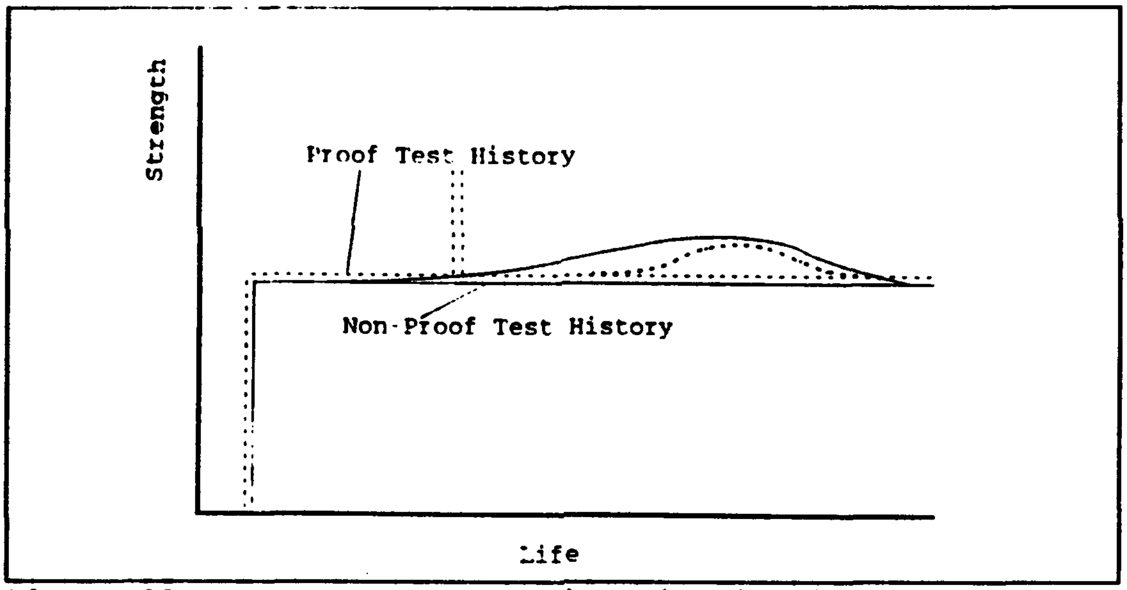

Figure 10. Post-Proof Test Life Distribution

Test stations vacated from proof testing are re-utilized by putting new samples on at the lowest load level to extend the prediction of the damage function.

The experimental procedure is described in Appendix B and the computer software used during the proof testing is listed in Appendix C.

Up to now, sufficient time has not yet elapsed for the observation of samples failed from either history. In the future, as the data becomes available, they may be progressively interpreted using the analytical techniques described in the following parametric studies, replacing simulated data with actual experimental data.

IV. DETERMINISTIC PARAMETRIC LIFE STUDY

A. FRACTIONAL LIFE

Despite the large replication of samples being tested in the experimental program, relatively few failures have been realized in time; i.e., failures classified as life data. This is because of the interaction between the strength scatter and the insensitivity of the breakdown rule, K, on the sustained stress level as shown in Figure 11. The high strength scatter can be attributed to the small diameter (approximately 6 microns) of the fiber filaments in that even a sub-micron imperfection represents a large percentage of the load carrying fiber cross section. The insensitivity of the breakdown rule to stress level can be attributed to inherent stable carbon micro-structure; that is, the addition of time does not contribute to the kinetics of micro-damage. These two characteristics makes experimental planning difficult. If a high sustained stress level is selected, a large portion of the samples will fail during the loading process (realized in strength). If a lower sustained stress level is chosen, because of the shallow slope of the strength degradation, an even longer life (logarithmic) is expected. The total effect is that mathematical and experimental ingenuity cannot reduce the time before the realization of data.

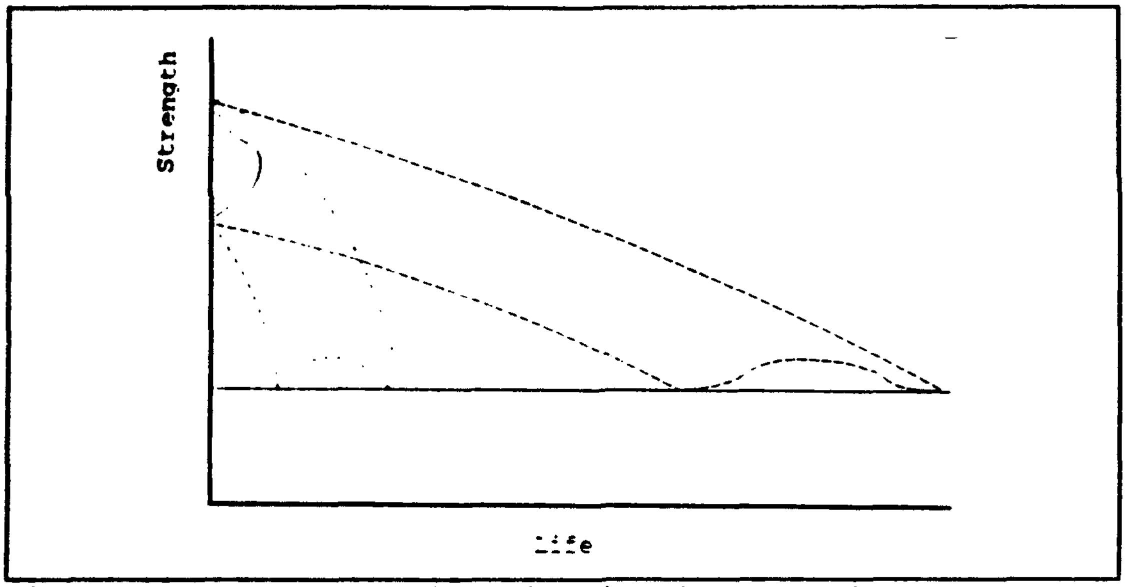

Figure 11. Strength Life Distribution Relation

In this section, a numerical parametric study is made on simulated data. The underlying function used in the Monte Carlo simulation is a two parameter, Weibull, weakest link distribution for fiber strength based on the justification in section II.B.3,

$$F(\sigma;\alpha,\beta)=1-\exp(-(\frac{\sigma}{\beta})^{\alpha})$$

The numerical values of α = 5 and β = 20 grams are based on previous test data by Englebert [Ref.10].

The breakdown rule is assumed to be of the power form,

$$K=(\frac{S(t)}{A})^{\rho}$$

and the justification is the stability of carbon minimizes all kinetic damage processes (the exponential rule). The slope of the power law, ρ = 40 is selected from experience obtained from other fibers. Other parameters used in the simulation such as loading rates are those used in actual testing.

Three stress histories were used, the first was a constant loading rate where the fibers were loaded until failure (Figure 12). Knowing the load rate and the failure strength, the failure time was calculated (Appendix D).

The second stress history considered was a constant loading rate and then maintained at a constant stress level (Figure 13). By calculating the fractional life used up in each portion of the stress history, the failure time was determined (Appendix E).

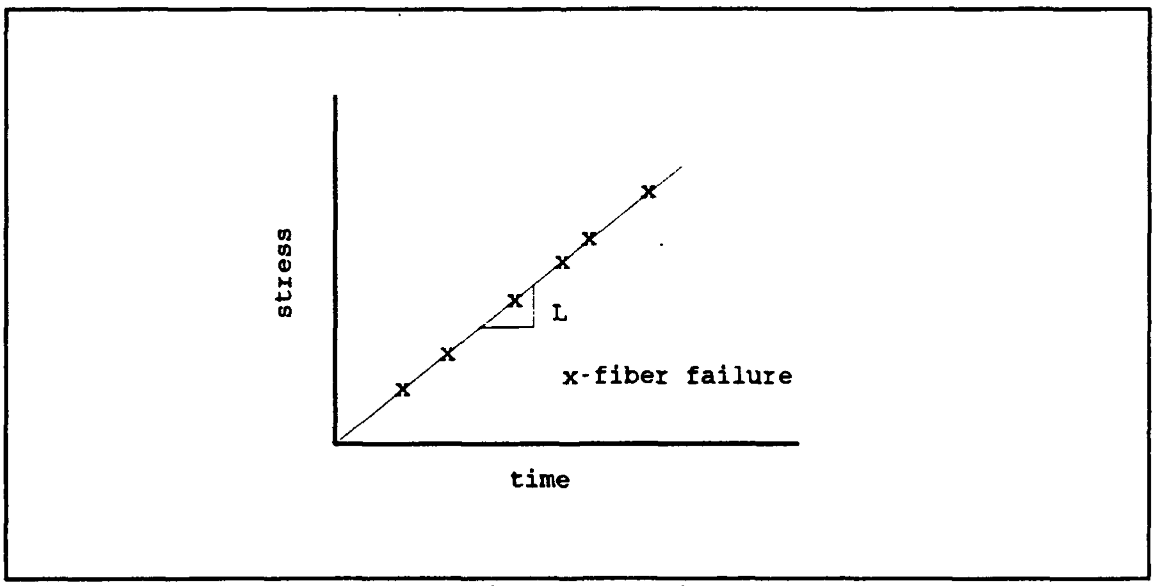

Figure 12. Constant Loading Rate History

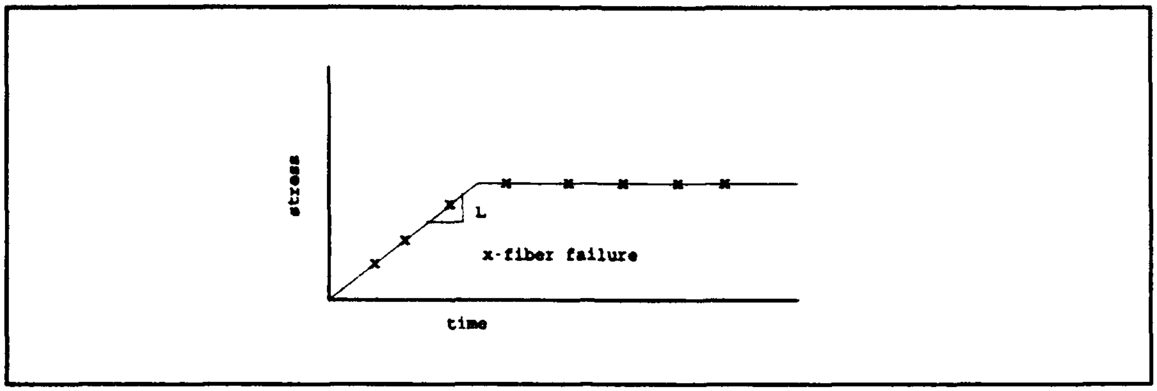

Figure 13. Stress Rupture History

Finally, a proof test history (Figure 14) was looked at and failure times were computed. The notation used in Figure 14 is defined in Appendix E.

As a fiber passes through each region in Figure 14, a portion of its life is consumed. Although each fiber experienced an identical stress history up to failure, the fractional life used up in each region varies greatly because of the dependence the intrinsic strength of the fiber. A weak fiber uses a large portion of its life just to attain the

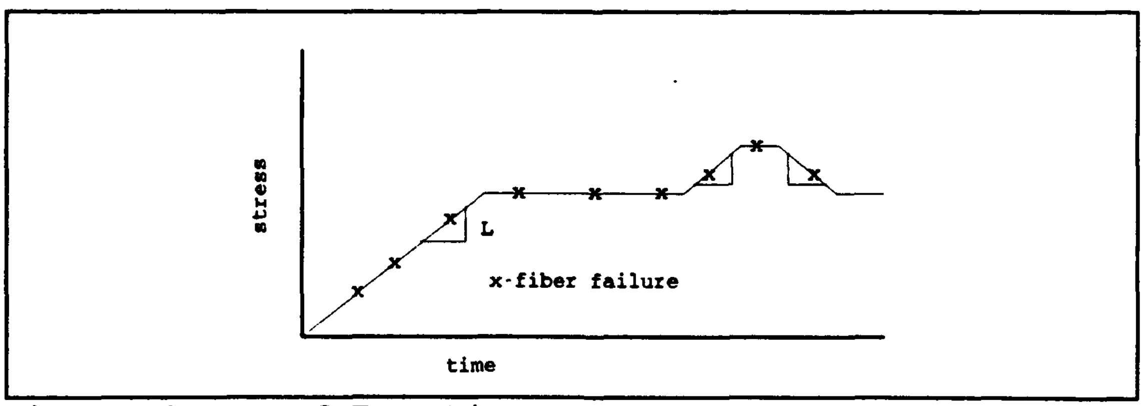

Figure 14. Proof Test History

sustained stress level. But the initial loading is small in proportion to the intrinsic strength of a strong fiber, thereby having little effect. Figures 15 and 16 show the fractional life consumed for the same three fibers, representing a low, medium and high intrinsic strength, during two different proof test histories. As seen in both figures, the weak fiber's entire life was consumed in just the initial loading process. While in contrast, the stronger fiber in the front of the graph, used a negligible amount of its intrinsic life reaching the proof load. By increasing the loading and unloading rate of the proof test portion from 0.8 and -0.8, in

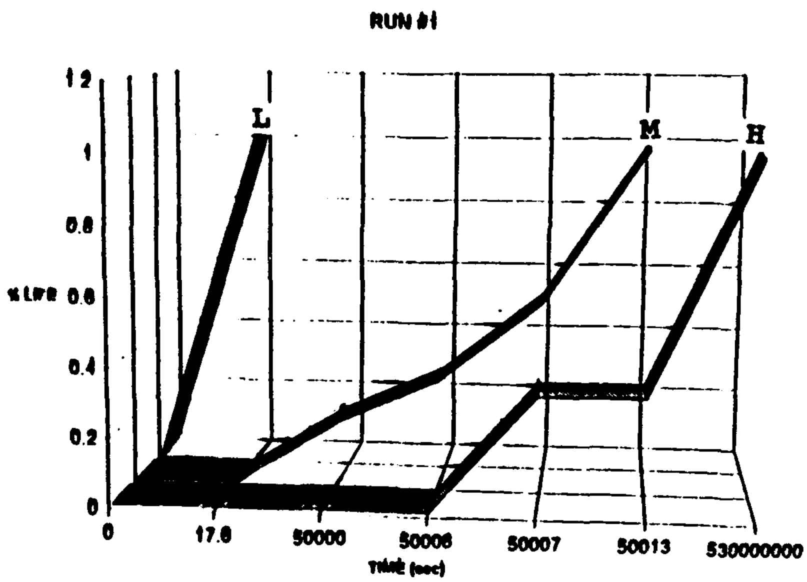

Figure 15. Fractional Life Run # 1

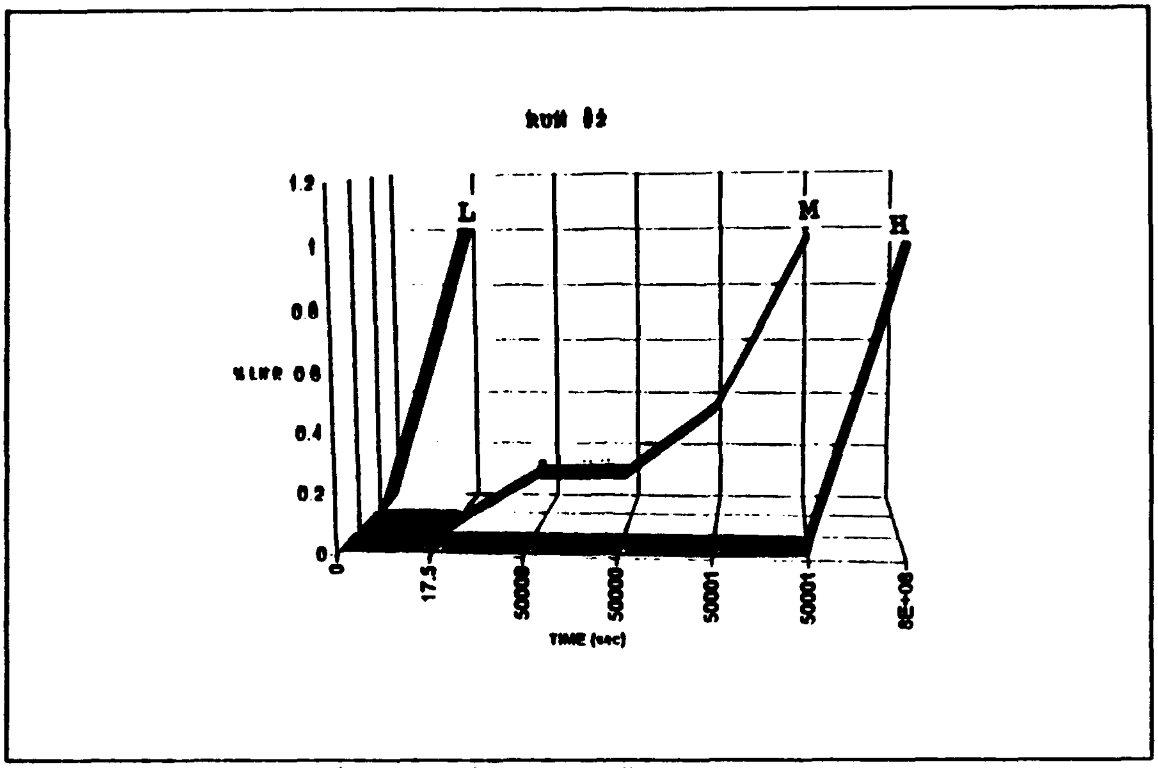

Figure 16. Fractional Life Run #2

run #1 to 50 and -50 (gm/sec), the time spent by the fiber in that region was decreased and the fractional life consumed was also reduced thereby allowing the fiber to last longer in real time. By manipulating the parameters, the fractional life consumed in any portion could be controlled in such a manner as to selectively screen out the weaker fibers. Appendix F contains a listing of the software used to calculate the fractional life along with a listing of the parameters used in each run.

V. POST-PROOF TEST SAFETY ZONE

As discussed in section III, for a period following the proof test, no failures occurred as compared to the non-proof test history. By causing the fibers to fail during proof testing, the time immediately following the proof test becomes a safety zone. A computer simulation was conducted to study the distribution of minimum times to first failure after the proof test, under varying parameters. A total of nine cases were conducted, each with 50 runs and each run simulated 2000 fibers. A histogram was then produced for each case in order to determine the sensitivity to parameter variation. The software used to conduct the simulation is listed in Appendix G along with a listing of the parameters for each run.

Figure 17 shows typical failure times for the non-proof tested and proof tested histories. Increasing the magnitude of the proof load for each sustained stress level caused the time to next failure to increase. The sustained stress level also played a role by causing the location of the histogram to shift. At lower sustained stress levels, the time to next failure was larger than at the higher loads. Figure 18 shows the histograms developed using a low sustained stress level and three levels of proof load; high, medium and low. As expected, by increasing the proof load, the time to next failure increased. The effect of screening out the weak fibers, those that would have failed in time, increases the safety zone tremendously. Figures 19 and 20 show similar trends for higher sustained stress levels. A high sustained stress level and a low proof load resulted in the minimum time before failure due to much of each fiber's fractional life being consumed just to reach the time the proof test was conducted. This in conjunction with a non-rigorous proof test, which did not screen out the weaker fibers, yielded the shorter times to next failure.

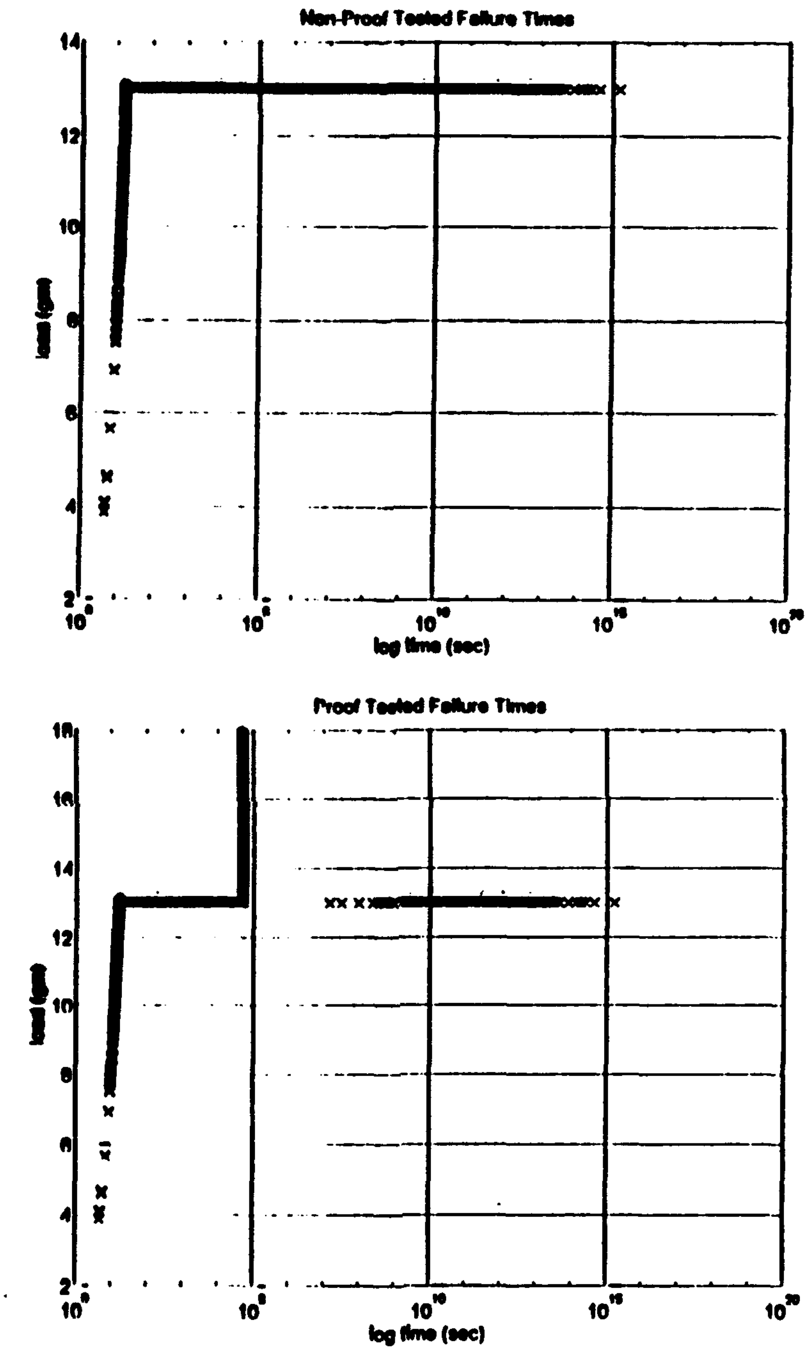

Figure 17. Stress History Failure Times

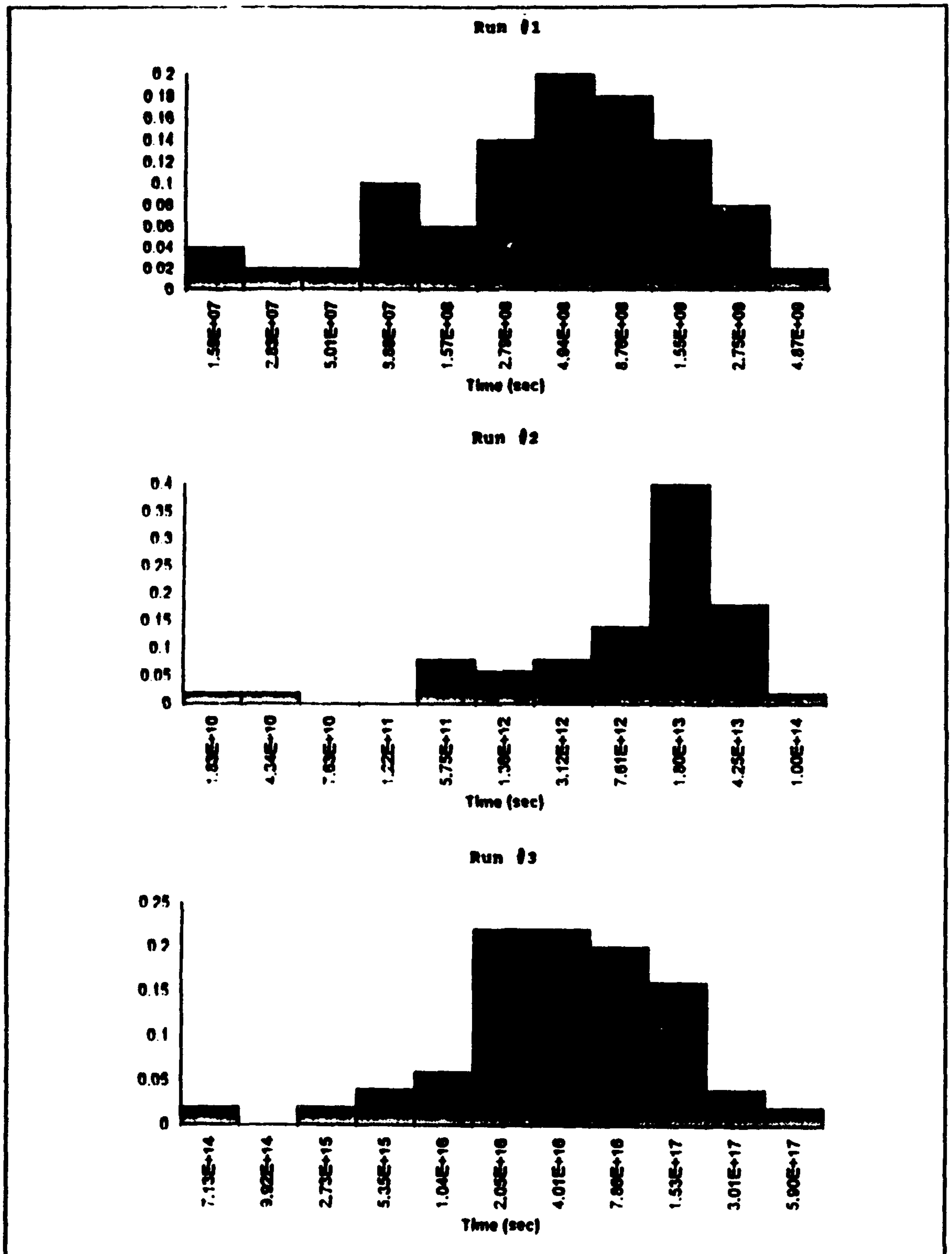

Figure 18. Post-Proof Test Safety Distribution Stress Level 1

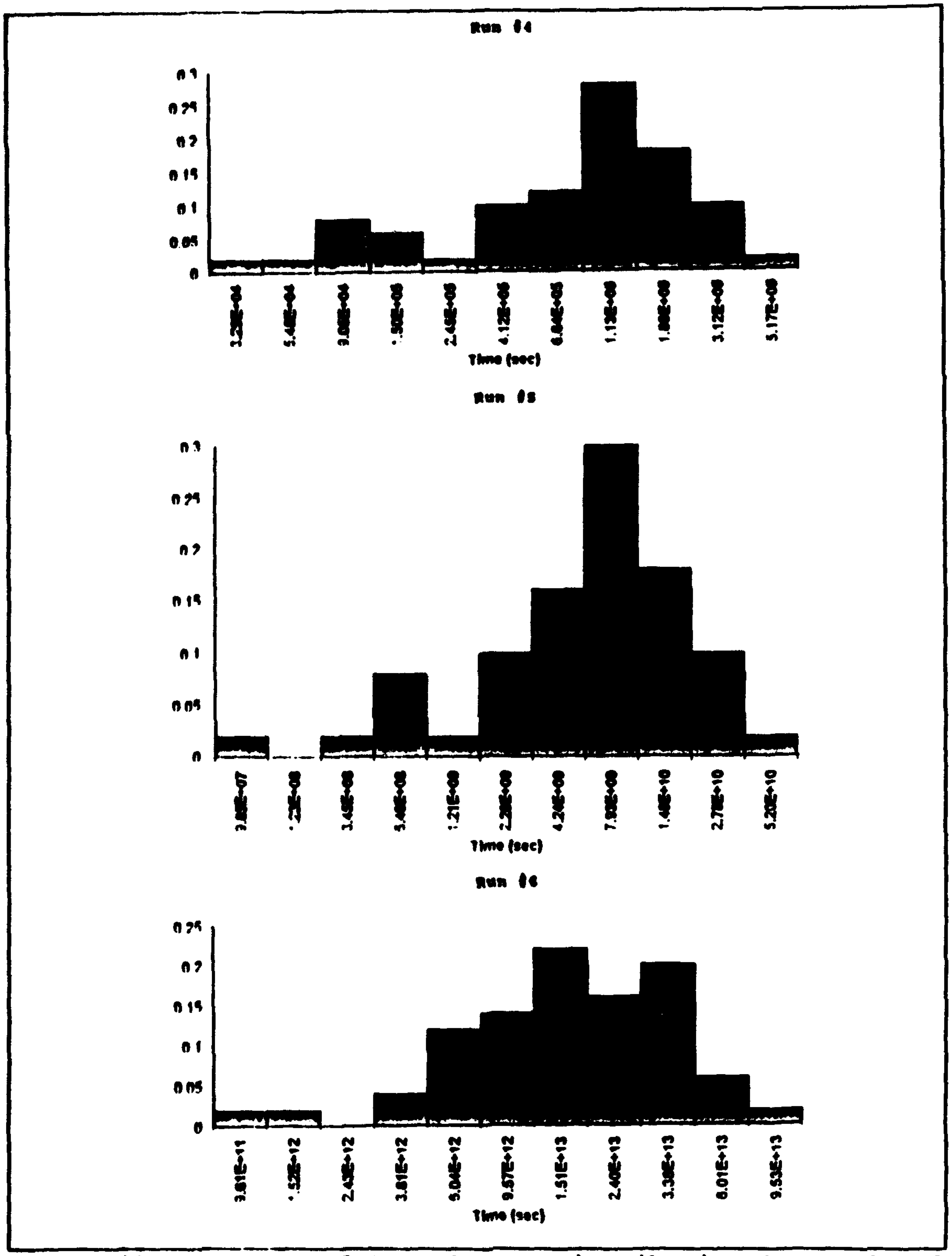

Figure 19. Post-Proof Test Safety Distribution Stress Level 2

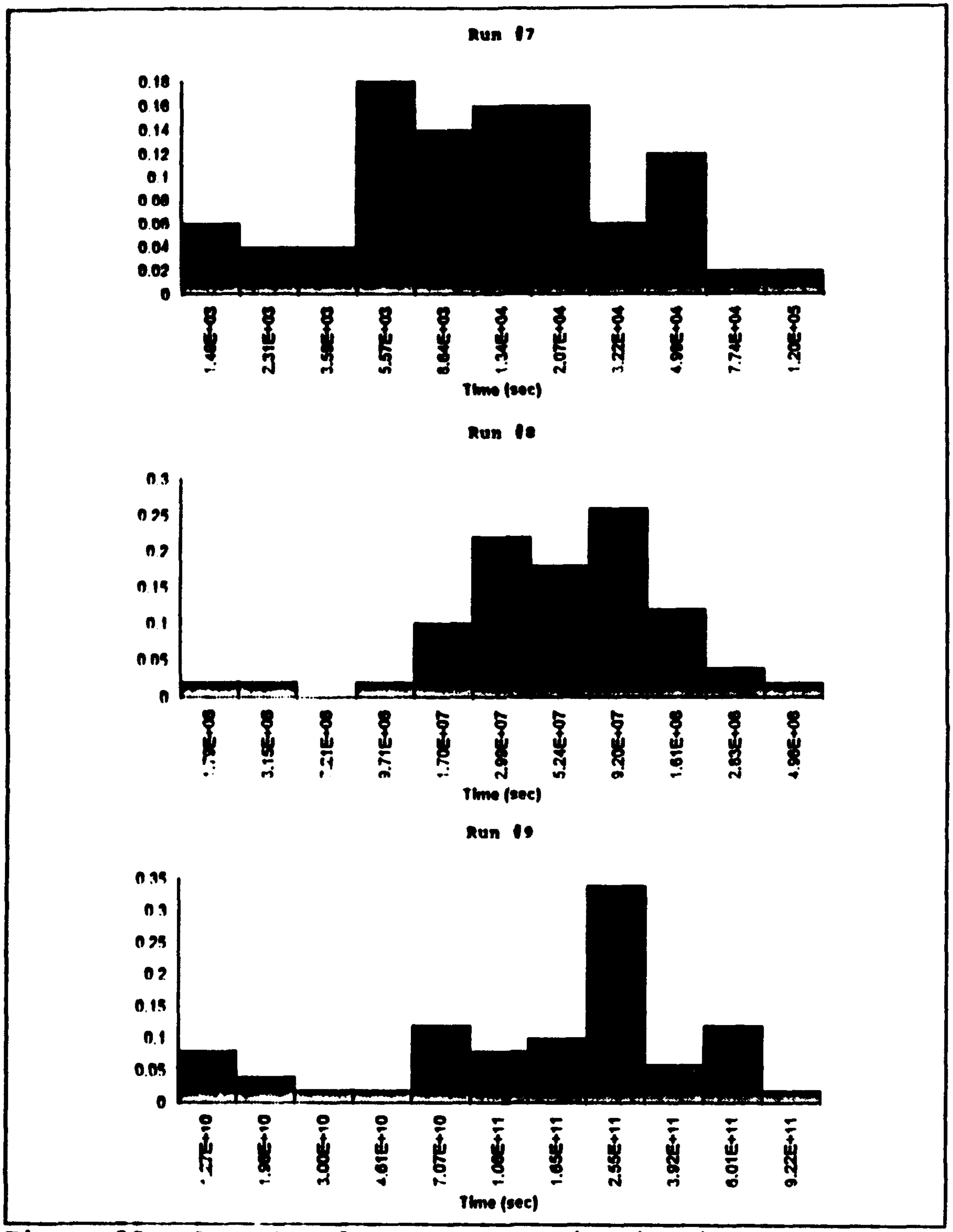

Figure 20. Post-Proof Test Safety Distribution Stress Level 3

VI. CONCLUSIONS AND RECOMMENDATIONS

The process of proof testing a material in order to ensure that it will not fail when in use at its service stress level is a much more complicated procedure than merely choosing an appropriate proof load. By understanding the role of each parameter in the strength-life relationship, a proof test method can be developed which may yield very precise results.

A specific recommendation is to include using a probabilistic approach with a model based on the pending data developed in this investigation.

APPENDIX A. REDUCED TIME CALCULATION

Given two stress histories as shown in Figure 21, what is the effect of sequencing of the stress levels and what effect does the slope have on the equivalent life?

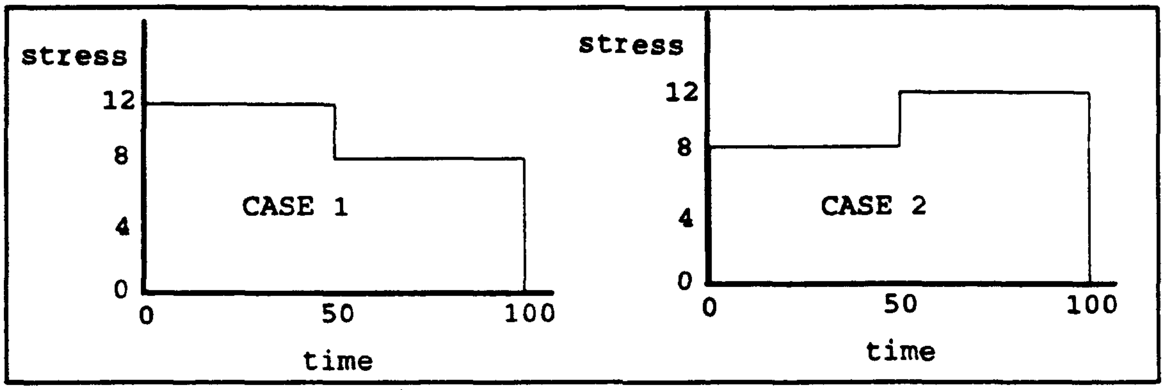

Figure 21. Stress History

The reduced time given by

$$T(\cdot) = \frac{1}{t}\int_{t_0}^{t_f} K(S(\xi))\, d\xi$$

and is a measure of the intrinsic life of a specimen. **K(•)** is the breakdown rule and S(ξ)) is the stress history that the specimen has undergone.

For this example, choose K(•) of the power form.

$$K(\cdot) = \left(\frac{S(\xi)}{A}\right)^{\rho}$$

For case 1:

$S(\xi) = 12$ for $0 \le \xi < 50$

$= 8$ for $50 \le \xi < 100$

$$T(\cdot) = \frac{1}{t}\int_{0}^{50}\left(\frac{12}{A}\right)^{\rho}d\xi + \frac{1}{t}\int_{50}^{100}\left(\frac{8}{A}\right)^{\rho}d\xi$$

and evaluating at the limits of integration gives

$$T(\cdot) = \frac{1}{tA^{\rho}}\{12^{\rho}(50) + 8^{\rho}(50)\}$$

For case 2:

$S(\xi) = 8$ for $0 \le \xi < 50$

$= 12$ for $50 \le \xi < 100$

$$T(\cdot) = \frac{1}{t}\int_{0}^{50}\left(\frac{8}{A}\right)^{\rho}d\xi + \frac{1}{t}\int_{50}^{100}\left(\frac{12}{A}\right)^{\rho}d\xi$$

and evaluating case two at the limits of integrations gives

$$T(\cdot) = \frac{1}{tA^{\rho}}\{8^{\rho}(50) + 12^{\rho}(50)\}$$

Therefore, sequence is not a factor.

Now consider case 1 to find the reduced time at an equivalent stress S_1.

$$T(\cdot) = \frac{1}{tA^{\rho}}\{12^{\rho}(50) + 8^{\rho}(50)\}$$

$$T(\cdot) = \frac{1}{tA^{\rho}}\{S_1^{\rho}(t_f)\}$$

because the life of the fiber is unity, the failure time, t_f, may be solved for at the stress level S_1.

APPENDIX B. PROOF TESTING PROCEDURES

Note: At least 24 hours prior to conducting the fiber loading, power up the HP-85 computer, HP-3497A Data Acquisition and the HP-62168 power supply (for the load cell) to allow the equipment to stabilize before any data is recorded. The excitation voltage to the load cell should be set to approximately 7.5 volts on the power supply dial, The voltage can be fined tuned using the HP-3497A as a readout.

1. Turn on the power supply to the elevator.
2. Turn the plotter.
3. Ensure that the drive plunger and the load plunger on the elevator operate smoothly and there are no air bubbles trapped in the plungers or the connecting line.
4. Ensure that there is a full supply of paper for both the HP-85 printer and the plotter. Also use fresh pens for the plotter.
5. Perform load cell calibration.
   Overview: The calibration procedure uses a program written by LT Bell to determine the slope and intercept of the calibration curve for the 150 gm load cell. Calibration weights are used

in even steps sizes to obtain a plot of the calibration curve. Weights ranging from 5 grams to 25 grams are normally used in 5 gram steps.

A. Insert Bell Fiber Test cassette in HP-85.

B. Type **clear** - this clears the screen.

C. Type **load "LDCALB"** - the computer searches the tape for the program.

D. Type **run**

E. Answer the prompts on the screen.

F. Enter number of calibration points required (usually 5).

G. Place calibration load on center of load cell.

   i. Enter load level.

   ii. When system stops reading data remove weight.

   iii. Repeat step G for each calibration point.

H. Enter plot axes data.

   i. Enter maximum load to be plotted on calibration curve.

   ii. Enter minimum load to be plotted on calibration curve.

   iii. Enter maximum x value (read off from tape--approx. -1.0).

   iv. Enter minimum x value (read off from tape--approx. -5.0).

I. If large plot is desired, set up plotter and follow cues on screen.

J. Repeat from step 5.D several times and compare the calibration coefficients obtained. The slope coefficient A will be used in the program LOAD5.

APPENDIX C. PROOF TESTING SOFTWARE

A. LOADCELL CALIBRATION PROGRAM

```
10 !   ** LDCALB**
20 !  JIM NAGEOTEE  OCT 26, 1986
30 CLEAR
40 DIM A(100), B(100), Z1(120), Z2(120)
50 DISP "LOAD CELL CALIBRATION"
60 CLEAR 709
70 DISP "NUMBER OF CALIBRATION POINTS, N1="
80 INPUT N1
90 FOR K = 1 TO N1
100 DISP "INPUT LOAD LEVEL"
110 INPUT L(K)
120 W = 23 @ E=5000
130 REM  :OUTPUT 709;"ARVR1VT3VD5VA0AE2"
140 ON TIMER# 1, E GOTO 240
150 I=1
160 OUTPUT 709; "AI0"
170 ENTER 709; A(I)
180 WAIT 10
190 OUTPUT 709; "AI10"
200 ENTER 709; B(I)
210 I = I +1
220 WAIT 23
230 GOTO 160
240 OFF TIMER # 1
250 N=I-1
260 P1=0 @ P2=0 @ Q1=0 @ Q2=0
270 X1=0 @ X2=0 @ B0 = 0
280 FOR I=N
290 B0=BO+B(I)
300 X1=X1+A(I)/B(I)
310 X2=X2+(A(I)/B(I))^2
320 P1=P1+A(I)
330 P2=P2+A(I)^2
340 Q1=Q1+B(I)
350 Q2=Q2+B(I)^2
360 NEXT I
370 E9=P1/N
380 D9=P2/N-E9^2
390 S9=E9^.5
400 C9=ABS(S9/E9*100)
410 E8=Q1/N
420 D8=Q2/N-E8^2
```

```
430 S8=D8^.5
440 C8=ABS(S8/E8*100)
450 X5(K)=X1/N
460 B0=B0/N
470 V(K)=X5(K)
480 X6=X2/N
490 D=X6-X5(K)^2
500 S1(K)=D^.5
510 C3=S1(K)/X5(K)
520 C3=C3*100
530 C3=ABS(C3)
540 PRINT "LOAD =';L(K);"gm"
550 PRINT "MEAN W=";X5(K);"V/V"
560 PRINT "S.D. V=";S1(K);"V/V"
570 PRINT "C.V. (%)=";C3
580 PRINT "L.C. OUTPUT VOLTAGE "
590 PRINT "MEAN V=";E9; "V"
600 PRINT "S.D. V=";S9: "V"
610 PRINT "C.V. (%)=";C9
620 PRINT "EXCITATION VOLTAGE "
630 PRINT "MEAN V=";E8; "V"
640 PRINT "S.D. V=";S8: "V"
650 PRINT "C.V. (%)=";C8
660 PRINT ""
670 NEXT K
680 X1=0 @ Y1=0
690 X3=0 @ X2=0
700 FOR K=1 TO N
710 X1=X1+V(K)
720 Y1=Y1=+L(K)
730 X3=X3+V(K)*L(K)
740 X2=X2+V(K)^2
750 NEXT K
760 X1=X1/N1
770 X2=X2/N1
780 X3=X3/N1
790 Y1=Y1/N1
800 D1=X2-X1^2
810 C1=(X3-X1*Y1)/D1
820 C2=(X2*Y1-X3*X1)/D1
830 PRINT "L=A*V+B"
840 PRINT "A= ";C1
850 PRINT "B= ";C2
860 R6=0
870 FOR K=1 TO N1
880 G2=(L(K)-C1*V(K)-C2)^2
890 R6=R6+G2
900 NEXT K
910 PRINT "RESIDUAL = ";R6
920 DISP "SCREEN GRAPH ROUTINE"
930 DISP "MAX. LOAD =";
```

```
940 INPUT Y2
950 DISP "MIN LOAD =";
960 INPUT Y1
970 U2=X5(1)
980 U1=X5(1)
990 FOR I=1 TO N1
1000 IF X5(I)>U2 THEN U2=X5(I)
1010 IF X5(I)<U1 THEN U1=X5(I)
1020 NEXT I
1030 PRINT "X MAX (1000V/V)= ";U2*1000
1040 PRINT "X MIN (1000V/V)= ";U1*1000
1050 DISP "INPUT MAX FOR X= ";
1060 INPUT U2
1070 DISP "INPUT MIN FOR X= ";
1080 INPUT U1
1090 FOR I=1 TO N1
1100 B1(I)=X5(I)*1000
1110 B2(I)=S1(I)*1000
1120 NEXT I
1130 S1=160/(U2-U1)
1140 S2=140/(Y2-Y1)
1150 FOR I=1 TO 5
1160 GRAPH @ CLEAR
1170 LDIR 0
1180 SCALE -48,208,-36,156
1190 XAXIS 0,32,0,160
1200 YAXIS 0,28,0,140
1210 PEN 1
1220 PENUP
1230 W1=160/(U2-U1)
1240 W2=140/(Y2-Y1)
1250 FOR I=0 TO 5
1260 U=U1+(U2-U1)/5*I
1270 P3=(U-U1)*W1
1280 MOVE P3,-10
1290 LABEL VAL$(U)
1300 NEXT I
1310 FOR I=0 TO 5
1320 Y=Y1+(Y2-Y1)/5*I
1330 Q3=(Y-Y1)*W2
1340 MOVE -23,Q3
1350 LABEL VAL$(Y)
1360 NEXT I
1370 MOVE 40, -23
1380 LABEL "1000*Vout/Vexc"
1390 DEG
1400 MOVE -29,25
1410 LDIR 90
1420 LABEL "Force (gm)"
1430 LDIR 0
1440 FOR I=1 TO N1
```

```
1450 Z1(I)=(B1(I)-U1)*W1
1460 Z2(I)=(L(I)-Y1)*W2-2
1470 MOVE Z1(I),Z2(I)
1480 LABEL "*"
1490 NEXT I
1500 G1=C1/1000
1510 FOR I=0 TO 101
1520 U=U1+(U2-U1)/100*I
1530 Y=G1*U+C2
1540 IF Y<Y1 OR Y>Y2 THEN 1580
1550 Z1(I)=(U-U1)*W1
1560 Z2(I)=(Y-Y1)*W2
1570 PLOT Z1(I),Z2(I)
1580 NEXT I
1590 COPY
1600 DISP "DO YOU WANT A HARD COPY ON PLOTTER?(Y/N)"
1610 INPUT K8$
1620 IF K8$="N" THEN 2170
1630 PRINT IS 10
1640 CONTROL 10,5 ;48
1650 OUTPUT 10 ;"IN;SP1;IP2400,1,600,8800,6900,:
1660 OUTPUT 10 ;"SC0,1000 ,0,1000"
1670 OUTPUT 10 ;"PU0,0PD0,1000,1000,1000,1000,0,0,0PU"
1680 W3=1000/(U2-U1)
1690 W4=1000/(Y2-Y1)
1700 OUTPUT 10 ;"SI0.2,0.3;TL1.5,0"
1710 FOR I=0 TO 5
1720 Y=Y1+(Y2-Y1)/5*I
1730 Y4=(Y-Y1)*W4
1740 Y=INT(Y)
1750 Y4=INT(Y4)
1760 OUTPUT 10 ;"PA 0,",Y4,"YT;"
1770 OUTPUT 10 ;"CP-5.-0.07;LB";Y;CHR$(3)
1780 NEXT I
1790 FOR I=0 TO 5
1800 U=U1+(U2-U1)*I/5
1810 U4=(U-U1)*W3
1820 U4=INT(U4)
1830 U=INT(U)
1840 OUTPUT 10 ;"PA";U4,",0;XT;"
1850 OUTPUT 10 ;"CP-1.3,-1;LB";U;CHR$(3)
1860 NEXT I
1870 OUTPUT 10 ;"SI.30,.42"
1880 OUTPUT 10 ;"PA400,0;CP-2,-2.3;LB1000*Vout/Vexc";CHR$(3)
1890 OUTPUT 10 ;"PA0,460;DI0,1;CP-2.6,2.6;LB FORCE (GM)";
     CHR$(3)
1900 OUTPUT 10 ;"DI;PU"
1910 FOR I =1 TO N1
1920 Z1(I)=(B1(I)-U1)*W3
1930 Z2(I)=(L(I)-Y1)*W4
1940 Z1(I)=INT(Z1(I))
```

```
1950 Z2(I)=INT(Z2(I))
1960 OUTPUT 10;"PA0,460;DI0,1;CP-2.6;2.6;LB FORCE (gm) ";
     CHR$(3)
1970 NEXT I
1980 OUTPUT 10 :"PU"
1990 FOR I=0 TO 101
2000 U=U1+(U2-U1)/100*I
2010 Y=G1*U+C2
2020 IF Y<Y1 OR Y>Y2 THEN 2060
2030 Z1(I)=(U-U1)*W3
2040 Z2(I)=(Y-Y1)*W4
2050 OUTPUT 10 ;"PA";Z1(I),Z2(I);"PD"
2060 NEXT I
2070 OUTPUT 10 ;"PU0,900,100,900"
2080 OUTPUT 10 ;"PU"
2090 OUTPUT 10 ;"SI.22,.38"
2100 DISP "ENTER THE LEGEND. ENTER '0' TO EXIT"
2110 INPUT P7$
2120 IF P7$="0" THEN 2150
2130 OUTPUT 10 ;"CP;LB";P7$;CHR$(3)
2140 GOTO 2100
2150 PRINTER IS 2
2160 DISP "END LDCALB"
2170 END
```

B. PROOF TEST PROGRAM

```
 10 !
 15 ! INCORPORATES PLOT ROUTINE*
 20 ! JIM NAGEOTTE  SEP 6,91
 30 !
 40 CLEAR @ DISP @ DISP
 45 DISP "FOR USE ON THE 150 GM
    CELL!"
 50 DISP "   QUIKLD PROGRM"
 55 A=-12621
 56 B=-23.291198677
 57 BEEP
 60 PRINTER IS 2
 70 SHORT A(55),B(55),P(600)
 80 PRINT "IF PROGRAM HALTS TYPE
     'CONT 100' TO RETURN TO MEN
    U"
 85 PRINT @ PRINT "MAKE SURE THA
    T LINE #251 IS CURRENT."
 90 PRINT @ PRINT
120 ON KEY# 2,"ADJ B" GOSUB 1000
130 ON KEY# 1,"DATE " GOSUB 210
140 ON KEY# 3,"LOAD" GOSUB 1320
150 ! ON KEY# 3, "WEIGH" GOSUB 10
    90
```

```
151 ! ON KEY# 5, "MX LOAD" GOSUB
    4000
155 ON KEY# 4, "PLOT" GOSUB 3000
160 ! ON KEY# 8, "END" GOTO 190
170 KEY LABEL
180 GOTO 120
190 CLEAR @ DISP @ DISP @ BEEP @
    DISP "  END OF HPLOR"
200 END
210 !  * INPUTS *
220 CLEAR @ DISP "ENTER THE DATE
    "
230 INPUT D$
251 W=4.8
280 CLEAR
290 RETURN
1000 ! * ADJUST B FOR 0 *
1010 CLEAR @ DISP @ DISP
1020 DISP "APPLY ZERO LOAD TO LO
     AD CELL"
1030 BEEP @ DISP
1040 GOSUB 1130
1050 B1=P1/23
1060 B=B-B1
1070 GOSUB 1185
1080 CLEAR @ RETURN
1090 !  * WEIGH *
1100 ! SHORT ROUTINE TO CHECK
1110 ! ACCURACY OF CALIBRATION
1120 CLEAR 709 @ CLEAR
1130 OUTPUT 709 ;"AI10"
1140 ENTER 709 ; V
1150 A1=A/V
1170 BEEP
1185 P1=0
1190 FOR I=1 TO 25
1200 OUTPUT 709 ;"AI0"
1210 ENTER 709 ; L
1220 P=L*A1+B
1230 P=INT(P*1000)/1000
1235 IF I <3 THEN 1260
1240 DISP P,
1250 P1=P1+P
1260 NEXT I
1270 DISP
1280 PRINT  "Vout=";V
1290 PRINT "LOAD =";INT(P1/23*10
     00)/1000;" gm"
1300 BEEP
1310 RETURN
1320 !  *  LOAD IT  *
```

```
1390 CLEAR @ PRINT @ PRINT @PRI
     NT @ PRINT
1400 PRINT D$
1403 DISP "ENTER THE SAMPLE#"
1405 INPUT S2$
1407 DISP "ENTER THE STATION #"
1409 INPUT S1
1410 DISP @ DISP @ DISP "PREPARE
     LOADER"
1420 DISP @ DISP "HIT 'CONT' WHE
     N READY."
1430 PAUSE
1440 BEEP @ CLEAR
1450 CLEAR 709
1460 OUTPUT 709 ; AI10"
1470 ENTER 709 ; V
1480 A1=A/V
1490 OUTPUT 709 ; "AI0"
1500 ENTER 709 ; L
1510 P=L*A1+B
1520 P=ABS(P*100/100)
1542 P=INT(P*1000)/1000
1543 BEEP
1544 PRINT @ PRINT "WEIGH MEASU
     RES";P
1550 DISP "WEIGH IS  ";P
1560 DISP "START LOADER AND HIT
     'CONT' SIMULTANEOUSLY"
1570 PAUSE
1580 C9=0 @ I=0 @ P3=W
1585 DISP @ DISP @ DISP "  LOAD
     ING"
1590 I=I+1
1600 OUTPUT 709 ; "AI0"
1610 ENTER 709 ; L
1620 P(I)=L*A1+B
1630 IF I<4 THEN 1590
1640 ! IF P(I)>P(I-1) THEN P4=P(
     I) +14.17
1645 IF P(I)<P3 THEN P3=P(I)
1650 IF P(I)<W*.9 THEN C9=1
1660 ! IF C9=1 AND P(I)>W*.95 TH
     EN GOTO 1690
1670 WAIT 25
1680 GOTO 1590
1690 CLEAR @ DISP @ DISP @ DISP
1700 BEEP 100,100
1750 P2=INT((W-P3)*100)/100
1760 DISP "FIBER BROKEN AT ";P2;
     "gms."
1770 PRINT S2$;" #";S1;" BROKEN
```

```
     AT ";P2;"gms."
1775 PRINT P2;"gms"
1780 CLEAR @ RETURN
1840 ! * TIMER *
1850 T1=TIME
1860 BEEP @ CLEAR @ DISP "TURN O
     FF LOADER" @ BEEP
1863 DISP @ DISP @ DISP "TIMING
     FOR TWO MINUTES."
1870 OUTPUT 709 ; "AI0"
1880 ENTER 709 ; L
1890 P=L*A1+B
1900 T2=TIME
1910 T3=T2-T1
1920 IF T3>120 THEN GOTO 2000
1930 IF P>W*.9 THEN GOTO 1950
1940 GOTO 1870
1950 ! * IT BROKE *
1960 CLEAR @ DISP @ DISP @ BEEP
     100,250
1970 DISP "FIBER BROKEN AT ";T3;
     " SEC."
1980 PRINT "FIBER #";S1;" BROKEN
     AT ";T3;" SECONDS."
1990 CLEAR @ RETURN
2000 ! * END OF TIME *
2010 CLEAR @ DISP @ DISP @ DISP
     @ DISP @ DISP @ DISP "FIBER
     OK"
2020 BEEP 50,200
2030 PRINT "FIBER #";S1;" INTACT
     "
2040 PRINT @ PRINT
2045 BEEP @ DISP 2 DISP "MAKE PL
     OT!" @ BEEP
2046 DISP @ DISP "HIT CONT" @ PA
     USE
2050 CLEAR @ RETURN
2060 END
3000 !     **PLOTTER**
3001 CLEAR
3003 BEEP @ FOR T=1 TO 100 @ NEX
     T @ BEEP @ DISP @ DISP @
     DISP "INSTALL PAPER IN PLOT
     TER!"
3004 DISP @ DISP "HIT CONT"
3006 PAUSE
3010 CLEAR
3020 Y2=5
3030 X2=I
3040 N=I
```

```
3050 S3=1000/X2
3060 S4=1000/Y2
3070 PRINTER IS 10
3080 CONTROL 10,5 ; 48
3090 OUTPUT 10 ;"IN;SP1;IP2400,1
     600,8800,6900;"
3100 OUTPUT 10 ;"SC0,1000,0,1000
     "
3110 OUTPUT 10 ;"PU0.0PD0,1000,1
     000,1000,1000.0.0.0PU"
3120 OUTPUT 10 ;"SI0.2,0.3;TL1.5
     ,0"
3130 FOR I=0 TO 5
3140 Y=INT(Y2/5*I)
3150 Y4=INT(Y*S4)
3160 OUTPUT 10 "PA 0,",Y4,"YT;"
3170 OUTPUT 10 ;"CP-5,-0.07;LB";
     Y;CHR$(3)
3180 NEXT I
3190 FOR I=1 TO 5
3200 X=X2/5*I
3210 X4=INT(X*S3)
3220 OUTPUT 10 ;"PA";X4,",0;XT;"
3230 OUTPUT 10 ;"CP-1.3-1;LB";X
     ;CHR$(3)
3240 NEXT I
3250 OUTPUT 10 ;"SI.30,.42"
3260 OUTPUT 10 ;"PA220,0;CP4,-2.
     3;LBData Point";CHR$(3)
3270 OUTPUT 10 ;"PA0,460;DI0,1;C
     P-2.6,2.60;LB LOAD (gm)";CH
     R$(3)
3280 PRINT "SP0"
3290 PRINT "SP2"
3300 FOR I=1 TO N
3310 Z1=INT(I*S3)
3315 P5=W-P(I)
3320 Z2=INT(P5*S4)
3330 OUTPUT 10 ; "PA",Z1,Z2;"PD"
3340 NEXT I
3350 OUTPUT 10 ;"PU0,900,100,900
     "
3360 OUTPUT 10 ;"PU"
3370 OUTPUT 10 ;"SI.22,.38"
3380 PRINT "SP0"
3390 OUTPUT 10 ;"SI.22,.38"
3400 PRINT "IN;SP1;PA3000,6500"
3410 DISP "ENTER ONE LINE LABEL"
3420 INPUT B$
3440 C$=D$
3460 A$=S2$
```

```
3470 OUTPUT 10 ;"CP;LB";A$;" ON
     #";S1;CHR$(3)
3480 OUTPUT 10 ;"CP;LB";B$;CHR$(
     3)
3490 OUTPUT 10 ;"CP;LB";C$;CHR$(
     3)
3495 ! OUTPUT 10 ;"CP;LB"; MAX
     LOAD IS ";P4
3500 PRINTER IS 2
3510 CLEAR
3520 RETURN
4000 P4=P4+14.17
4005 DISP "MAX LOAD ON FIBER = "
     ;P4
4010 RETURN
```

APPENDIX D. REDUCED TIME PARAMETERS

It is assumed that the failure times of the fibers can be modeled by a Weibull distribution as

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\beta_t}\right)^{\alpha_t}\right)$$

where t is the independent variable, β_t is the location parameter and α_t is the shape parameter.

To understand the parameters associated with the reduced time, consider a stress rupture history where the fiber is imagined to be instantaneously loaded to a sustained stress level S_1 until failure at time t_f. Using a breakdown rule of the power law form, the reduced time is

$$T(\cdot) = \frac{1}{t}\int_0^{t_f}\left(\frac{S_1}{A}\right)^{\rho} d\xi$$

After integration,

$$T(\cdot) = \frac{t_f}{t}\left(\frac{S_1}{A}\right)^{\rho}$$

The reduced time may be substituted into the failure distribution as stated in section II.B.3, yielding

$$F(\cdot) = 1 - \exp\left(-\left(\left(\frac{t_f}{t}\right)\left(\frac{S_1}{A}\right)^{\rho}\right)^{\alpha}\right)$$

and set equal to the Weibull distribution above.

$$\left(\frac{t_f}{\hat{t}}\left(\frac{S_1}{A}\right)^{\rho}\right)^{a} = \left(\frac{t_f}{\beta_t}\right)^{\alpha_t}$$

by comparing exponents, $a = \alpha_t$, and rearranging gives

$$\frac{\beta_t}{\hat{t}}\left(\frac{S_1}{A}\right)^{\rho} = 1$$

If a deterministic approach is taken, β_t may be replaced by simply t_f, the failure time. If $\hat{t}$ is chosen to equal t_f, then A is the intrinsic strength at time $\hat{t}$. The parameter ρ is simply the slope of the breakdown function on a log-log plot.

APPENDIX E. PROOF TEST STRESS HISTORY

The proof test history is shown below and is divided into six regions as described.

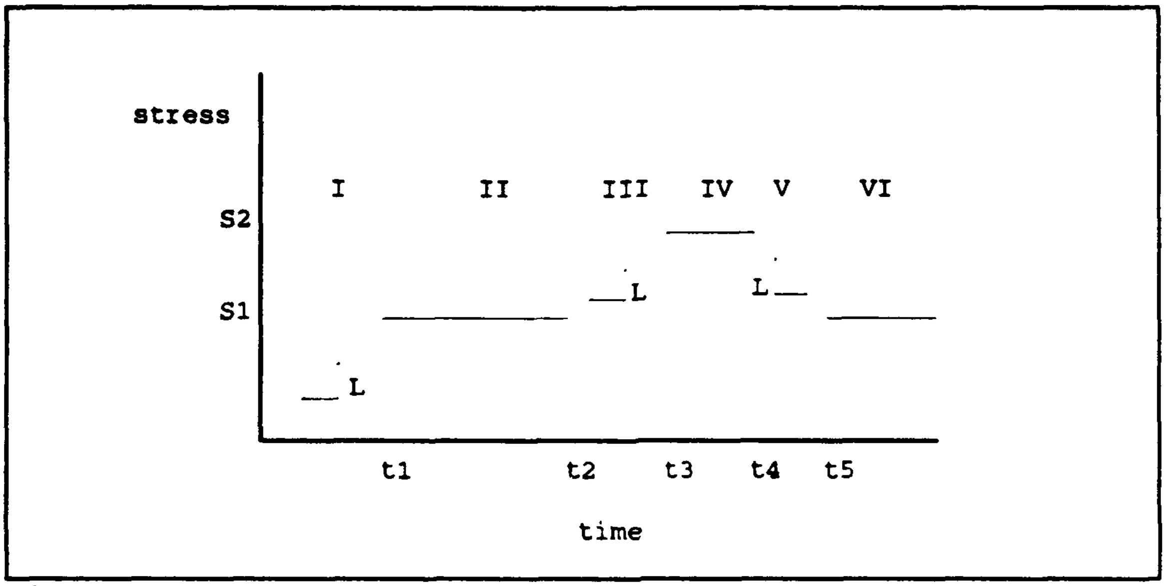

Figure 22. Proof Test Stress History

$$
\begin{aligned}
S(t) &= L_1 t && ;\ 0 \le t < t_1 && \text{Region I}\\
&= S_1 && ;\ t_1 \le t < t_2 && \text{Region II}\\
&= L_2\ (t-t_2) + S_1 && ;\ t_2 \le t < t_3 && \text{Region III}\\
&= S_2 && ;\ t_3 \le t < t_4 && \text{Region IV}\\
&= L_3\ (t-t_4) + S_2 && ;\ t_4 \le t < t_5 && \text{Region V}\\
&= S_1 && ;\ t > t_5 && \text{Region VI}
\end{aligned}
$$

Using a breakdown rule of the power form and the stress history as above, the fractional life used in each region is the sum of the

$$T(\cdot)=\frac{1}{t}\int_{0}^{t_1}\left(\frac{L_1 t}{A}\right)^{\rho}d\xi+\frac{1}{t}\int_{t_1}^{t_2}\left(\frac{S_1}{A}\right)^{\rho}d\xi$$

$$+\frac{1}{t}\int_{t_2}^{t_3}\left(\frac{L_2(t-t_2)}{A}\right)^{\rho}d\xi+\frac{1}{t}\int_{t_3}^{t_4}\left(\frac{S_2}{A}\right)^{\rho}d\xi+\frac{1}{t}\int_{t_4}^{t_5}\left(\frac{L_3(t-t_4)}{A}\right)^{\rho}d\xi+\frac{1}{t}\int_{t_5}^{t_f}\left(\frac{S_1}{A}\right)^{\rho}d\xi$$

integrals up to the failure time.

Performing and evaluating at the limits of integration yields,

$$T(\cdot)=\frac{1}{t}\left(\frac{L_1}{A}\right)^{\rho}\frac{t_1^{\rho+1}}{(\rho+1)}+\frac{1}{t}\left(\frac{S_1}{A}\right)^{\rho}(t_2-t_1)$$

$$+\frac{1}{t}\frac{A}{L_2(\rho+1)}\left(\left(\frac{(L_2(t_3-t_2)+S_1)}{A}\right)^{\rho+1}-\left(\frac{S_1}{A}\right)^{\rho+1}\right)$$

$$+\frac{1}{t}\left(\frac{S_2}{A}\right)^{\rho}(t_4-t_3)$$

$$+\frac{1}{t}\frac{A}{L_3(\rho+1)}\left(\left(\frac{(L_3(t_5-t_4)+S_2)}{A}\right)^{\rho+1}-\left(\frac{S_2}{A}\right)^{\rho+1}\right)$$

$$+\frac{1}{t}\left(\frac{S_1}{A}\right)^{\rho}(t_f-t_5)$$

APPENDIX F.

A. SIMDATA

```
% PROGRAM SIMDATA
Written by LT Greg Morin
% This program produces simulated data which can be used for
analysis of
% of a Weibull distribution model.  Inputs include the desired
population
% size and the underlying shape and location parameters, N,
alpha, and beta
% respectively.  Outputs include the following column vectors:
%                    X=[population]
%                   xi=[exact data]
%                   xr=[right censored data]
%                   Fstarx=[underlying F* values for population]
%                   Fstar=[Expected Ranking F* values]
clear
clg
N=input('Enter the population size:  ');
a=input('Enter desired underlying alpha:   ');
b=input('Enter desired underlying beta:   ');
% Function to simulate data and plot fstar for expected and true
rank
% of the population.
[X,Fstar,Fstarx]=populat(N,a,b);
hold on
% Function to determine exact and right censor data
[xi,Fstrc,m,xr]=rightcns(X,N,Fstar);
hold off
save xi xi /ascii
save xr xr /ascii
save X X /ascii
save Fstarx /ascii
save Fstar /ascii
```

B. FRACTIONAL LIFE

```
%********** Program Name: Eqvl_1, written for MATLAB **********
Written by LT Joe Woodward
clear                   %CLEAR ALL VARIABLES IN WORKSPACE
format long e           %SET OUTPUT FORMAT TO 16 DIGITS

%       VARIABLES DEFINED
%
```

```
%  A           intrinsic strength of the fiber
%  x           stress level that fiber was realized at during
%              ramp loading
%  N           the size of the sample
%  ldot1       the initial loading rate used on the fibers
%                (gm/sec)
%  ldot2       the loading rate used on the proof test (gm/sec)
%  ldot3       the unloading rate used on the proof test (gm/sec)
%  teehat      intrinsic time used to determine strength
%  rho         the slope of the breakdown law
%  S1          sustained stress level
%  S2          stress level of proof test
%  time1       time sustained stress level is reached
%  time2       time proof test begins
%  time3       time proof load is attained
%  time4       time proof load is removed
%  time5       time sustained stress level is reached after
%              proof load
%  time6       duration of proof load
%  tnptf       failure time of non-proof tested fibers
%  tptf        failure time of proof tested fibers
%  sf          non-proof tested fiber failure stress
%  ssf         proof tested fiber failure stress
%  l,l1,l2,l3
%  l4,l5       arrays that store the fractional life consumed
%                during each region of the proof test stress
%                history. l is how much life was used during the
%                initial loading, l1 the life used up to proof
%                loading at the sustained stress level, etc.
%  l6          the total life consumed by each fiber.  Will equal
%                unity when the fiber fails.

% Load the simulated realized stress values
load x

% The following section asks for inputs from the operator for use
% in the program.
ldot1  = input('Enter the initial loading rate for the fibers
         (gm/sec), ldot1:  ');
ldot2  = input('Enter the loading rate for the proof test
         (gm/sec), ldot2:  ');
ldot3  = input('Enter the unloading rate for the proof test
         (gm/sec), ldot3:  ');
rho    = input('Enter the slope of the breakdown law, rho:  ');
teehat = input('Enter the intrinsic time, teehat:  ');
S1     = input('Enter desired sustained stress level, S1:  ');

% CALCULATE THE TIME THAT THE SUSTAINED STRESS IS REACHED
time1 = S1/ldot1;
```

```
% DETERMINE THE SAMPLE SIZE (NUMBER OF X VALUES LOADED)
N=length(x);

% THIS LOOP FINDS THE INTRINSIC STRENGTH OF EACH SAMPLE, THE LOOP
% IS REPEATED N NUMBER OF TIMES
for i=1:N
   A(i) = ((x(i)^(rho+1))/(teehat*ldot1*(rho+1)))^(1/rho);

% FIND THE FAILURE TIME OF EACH FIBER DURING RAMP LOADING
   t_ramp(i) = x(i)/ldot1;
end

% SET THE INTRINSIC LIFE OF EACH FIBER TO UNITY
tau=1.0;

% CLEAR ANY GRAPHS AND THEN PLOT THE RAMP HISTORY (FAILURE TIME %
% VS. LOAD)
clg
plot(t_ramp,x,'rX'),grid
xlabel('time (sec)'),ylabel('load (gm)')
title('Fiber Failure Under a Constant Loading Rate');
pause

% THIS LOOP IS FOR THE NON-PROOF TESTED HISTORY
  for j = 1:N
  tnptf = t_ramp(j);
  sf = ldot1*tnptf;

% IF THE FAILURE TIME OF THE FIBER IS GREATER THAN THE TIME AT
% WHICH SUSTAINED STRESS LEVEL IS REACHED, THEN COMPUTE THE
% INTRINSIC STRENGTH AND THE FAILUR TIME GIVEN THAT THE FIBER
% SURVIVED AT LEAST UNTIL THE SUSTAINED STRESS LEVEL.  THE STRESS
% LEVEL AT WHICH THE FIBER FAILED AT IS THE SUSTAINED STRESS
% LEVEL, S1.
       if tnptf>=time1
         a=(((ldot1/A(j))^rho)*((time1^(rho+1))/(rho+1)));
         tnptf = (tau*teehat-a)*((A(j)/S1)^rho) + time1;
         sf = S1;
       end

% FILL THE ARRAYS TNPT(J) AND S(J) WITH THE FAILURE TIMES AND
% CORRESPONDING STRESSES FOR PLOTTING.
  tnpt(j)=tnptf;
  s(j) = sf;
  end

% PLOT THE NON-PROOF TESTED FIBERS ON SEMILOG (IN TIME) VS.
% FAILURE STRESS
semilogx(tnpt,s,'y+')
xlabel('log time (sec)'),ylabel('stress'),grid
hold
```

```
pause

% THIS SECTION ASKS FOR INPUT REGARDING THE PROOF TEST.
dS      = input('Enter proof load magnitude, Ds:  ');
time2   = input('Enter the time the proof load is conducted (sec),
          time2:  ');
time6   = input('Enter the duration of the proof load (sec),
          time6:  ');

% COMPUTE THE TIME THE PROOF LOAD IS REACHED (TIME3).
time3 = time2 + dS/ldot2;

% COMPUTE THE TIME THAT THE UNLOADING OF THE PROOF TEST STARTS
% (TIME4), WHERE TIME6 IS THE DWELL TIME, i.e., THE DURATION THAT
% THE PROOF LOAD IS MAINTAINED.
time4 = time3 + time6;

% COMPUTE THE TIME THAT THE ORIGINAL SUSTAINED STRESS LEVEL IS
% REACHED AFTER UNLOADING THE PROOF LOAD (TIME5).
% proof load
time5 = time4 + (Ds/(-ldot3));

% S2 IS THE MAGNITUDE OF THE PROOF LOAD, ORIGINAL SUSTAINED
% STRESS LEVEL PLUS THE INCREMENTAL PROOF LOAD.
S2 = S1 + ds;

% THIS LOOP IS FOR THE PROOF TESTED FIBERS.
for j = 1:N
   tptf = t_ramp(j);
   ssf = ldot1*tptf;

%**********************REGION I**********************************

% IF THE FAILURE TIME OF THE FIBER IS LESS THAN THE TIME AT
% WHICH THE SUSTAINED STRESS LEVEL IS REACHED, THEN COMPUTE THE
% FRACTIONAL LIFE, (l(j)), CONSUMED GIVEN THAT THE FIBER FAILED
% ON LOADING.
     if tptf<=time1
        l(j)=(1/(teehat*(rho+1)))*((ldot1/A(j))^rho)...
         *(tptf^(rho+1));
     else

% IF THE FAILURE TIME IS GREATER THAN THE THE TIME AT WHICH THE
% SUSTAINED STRESS LEVEL IS REACHED, THEN COMPUTE THE FRACTIONAL
% LIFE BASED ON TIME1
          l(j)=(1/(teehat*(rho+1)))*((ldot1/A(j))^rho)...
          *(time1^(rho+1));
     end
     l6(j)=l(j);
```

```
%******************REGION II**********************************

% IF THE FAILURE TIME IS GREATER THAN THE TIME AT WHICH THE
% SUSTAINED STRESS LEVEL IS REACHED, THEN COMPUTE THE FAILURE
% TIME GIVEN A NEW STRESS HISTORY, i.e., THE FIBER SURVIVED
% LOADING AND SPENT SOME OF ITS LIFE UNDER A SUSTAINED CONSTANT
% LOAD, S1.  THE FAILURE TIME IS COMPUTED BY SUBTRACTING THE
% FRACTIONAL LIFE CONSUMED DURING THE INITIAL LOADING PROCESS
% FROM THE TOTAL LIFE TAU.
  if tptf>time1
      tptf = (tau-l(j))*(teehat*(A(j)/S1)^rho) + time1;
      ssf = S1;

        if tptf<=time2
         l1(j)=(1/teehat)*((S1/A(j))^rho)*(tptf-time1);
        else
         l1(j)=(1/teehat)*((S1/A(j))^rho)*(time2-time1);
        end
      l6(j)=l(j)+l1(j);

%******************REGION III*********************************

% EACH IF STATEMENT CHECKS TO SEE IF THE FAILURE TIME FALLS
% BETWEEN THE START OF A NEW REGION AND THE START OF THE NEXT
% REGION.  IN THIS CASE, IS THE FAILURE TIME BETWEEN THE START OF
% THE SUSTAINED STRESS REGION AND THE START OF THE PROOF LOADING
% REGION.  IF IT IS, THE FAILURE TIME IS COMPUTED BASED ON THE
% GERMAIN STRESS HISTORY AND THE FRACTIONAL LIFE IS COMPUTED
% BASED ON THAT FAILURE TIME.  IF THE FAILURE TIME IS GREATER
% THAN WHEN THE NEXT REGION STARTS (IN THIS CASE THE PROOF
% TESTING) THAN THE FRACTIONAL LIFE CONSUMED IS BASED ON THE
% ABSOLUTE TIME SPENT UNDER THE SUSTAINED LOAD.
     if tptf>time2
        tptf=(((tau-l(j)-l1(j))*(teehat*ldot2*(rho+1)/A(j))...
             +((S1/A(j))^(rho+1)))^(1/(rho+1))-(S1/A(j)))...
             *(A(j)/ldot2)+time2;

% THE FAILURE STRESS WILL BE BETWEEN THE ORIGINAL SUSTAINED
% STRESS LEVEL, S1 AND THE PROOF TEST LEVEL S2.
        ssf = ldot2*(tptf-time2)+S1;

        if tptf<=time3
          l2(j)=(1/teehat)*((((ldot2*(tptf-time2)...
              +S1)/A(j))^(rho+1)-((S1/A(j))^(rho+1)))*(A(j)/...
              (ldot2*(rho+1))));
        else
          l2(j)=(1/teehat)*((((ldot2*(time3-time2)...
              +S1)/A(j))^(rho+1)...
              -((S1/A(j))^(rho+1)))*(A(j)/(ldot2*(rho+1))));
        end
```

```
        l6(j)=l(j)+l1(j)+l2(j);

% ***************REGION IV***************************************
          if tptf>time3
            tptf =(tau-l(j)-l1(j)-l2(j))*(teehat*(A(j)...
                 /S2)^rho)+time3;
            ssf = S2;

            if tptf<=time4
              l3(j)=(1/teehat)*(((S2/A(j))^rho)*(tptf-time3));
            else
             l3(j)=(1/teehat)*(((S2/A(j))^rho)*(time4-time3));
            end
            l6(j)=l(j)+l1(j)+l2(j)+l3(j);

%******************REGION V***************************************
              if tptf>time4
                tptf=-(((tau-l(j)-l1(j)-l2(j)-l3(j))...
                     *(teehat*(-ldot3)*(rho+1)/A(j))+((S2/A(j))...
                     ^(rho+1)))^(1/(rho+1))-(S2/A(j)))*(A(j)/...
                     ldot3)+time4;
                ssf = S2+ldot3*(tptf-time4);

                if tptf<=time5
                  l4(j)=-(1/teehat)*((((ldot3*(time4-tptf)...
                        +S2)/A(j))^(rho+1))-((S2/A(j))^(rho+1...
                        )))*(A(j)/(ldot3*(rho+1)));
                 else
                l4(j)=-(1/teehat)*((((ldot3*(time4-time5)...
                        +S2)/A(j))^(rho+1))-((S2/A(j))^(rho+1...
                        )))*(A(j)/(ldot3*(rho+1)));
                end
                  l6(j)=l(j)+l1(j)+l2(j)+l3(j)+l4(j);

%******************REGION VI**************************************
                  if tptf>time5
                    tptf=(tau-l(j)-l1(j)-l2(j)-l3(j)-l4(j))...
                          *(teehat*(A(j)/S1)^rho) +time5;
                    ssf= S1;
                    l5(j)=(1/teehat)*((S1/A(j)...
                          )^rho)*(tptf-time5);
                    l6(j)=l(j)+l1(j)+l2(j)+l3(j)...
                          +l4(j)+l5(j);
                    end
            end
          end
      end
   end
tpt(j)=tptf;
ss(j)=ssf;
end
```

```
% PLOT THE PROOF TESTED STRESS HISTORY, FAILURE TIME VS. STRESS
semilogx(tpt,ss,'rX')
save SS.m ss -ascii
save TPT.m tpt -ascii
save S.m s -ascii
save TNPT.m tnpt -ascii
format short e

% THE MATRIX T IS THE FRACTIONAL LIFE OF EACH FIBER CONSUMED
% DURING EACH REGION AND THE FAILURE TIME.
T=[l' l1' l2' l3' l4' l5' l6' tpt];
save T.txt T -ascii
save T.m T
```

C. PARAMETERS USED IN DETERMINISTIC LIFE STUDY

For all runs, $\alpha = 5$, $\beta = 20$, $\rho = 40$, $\hat{t} = 1$ and $t_2 = 50000$.

Run #1: $L_1 = .8$, $L_2 = .8$, $L_3 = -.8$, $S_1 = 14.1$, $S_2 = 18.6$, $t_{dwell} = 1$.

Run #2: $L_1 = .8$, $L_2 = 50$, $L_3 = -50$, $S_1 = 14.1$, $S_2 = 18.6$, $t_{dwell} = 1$.

APPENDIX G.

A. POST-PROOF TEST SOFTWARE

```
%   ********* Post-Proof Test Software ********
Written by LT Joe Woodward
clear
format long e

%       VARIABLES DEFINED
%
%
% x       stress level that fiber was realized at during
%         ramp loading
% n       the size of the sample
% ldot       the loading rate used on the fibers (gm/sec)
% teehat     intrinsic time used to determine strength
% rho     the slope of the breakdown law
% S1      sustained stress level
% S2      stress level of proof test
% time1      time sustained stress level is reached
% time2      time proof test begins
% time3      time proof load is attained
% time4      time proof load is removed
% time5      time sustained stress level is reached after
%         proof load
% time6      duration of proof load


n      = 2000;%input('Enter the number of samples to be
calculated, N:  ');
alpha  = 5;%input('Enter desired underlying alpha:   ');
beta   = 20;%input('Enter desired underlying beta:   ');
ldot1  = .8;%input('Enter the initial loading rate for the fibers
(gm/sec), ldot1:  ');
ldot2  = .8;%input('Enter the loading rate for the proof test
(gm/sec), ldot2:  ');
ldot3  = -.8;%input('Enter the unloading rate for the proof test
(gm/sec), ldot3:  ');
rho    = 40;%input('Enter the slope of the breakdown law, rho:
');
teehat = 1;%input('Enter the intrinsic time, teehat:  ');
S1     = 7;%input('Enter desired sustained stress level, S1:  ');
Ds     = 3;%input('Enter proof load magnitude, Ds:  ');
time2  = 50000;%input('Enter the time the proof load is conducted
(sec), time2:  ');
time6  = 1;%input('Enter the duration of the proof load (sec),
time6:  ');
```

```
% time that sustained stress level is reached
time1 = S1/ldot1;

% time that proof load is reached
time3 = time2 + Ds/ldot2;

% time that unloading of proof load starts
time4 = time3 + time6;

% time that original sustained stress level is reached after
unloading
% proof load
time5 = time4 + (Ds/(-ldot3));

S2 = S1 + Ds;
%*******outside loop
deltime=zeros(1,50);
for jj=1:50
LL=1;
for j=1:n
Fx=rand;
x=beta*(-log(1-Fx))^(1/alpha);


%  Find the intrinsic strength for each fiber at teehat

   A = ((x^(rho+1))/(teehat*ldot1*(rho+1)))^(1/rho);

%  Find the failure time of each fiber during ramp loading

   t_ramp = x/ldot1;

%  Set the reduced time (Life) of each fiber

   tau = 1.0;

%    **** NON-PROOF TESTED FIBERS ****


   tnptf = t_ramp;
   sf = ldot1*tnptf;

   if tnptf<=time1
        lx=(1/(teehat*(rho+1)))*((ldot1/A)^rho)*(tnptf^(rho+1));
        else
lx=(1/(teehat*(rho+1)))*((ldot1/A)^rho)*(time1^(rho+1));
   end
     lx6(j)=lx;

   if tnptf>time1
```

```
        tnptf = (tau-lx)*(teehat*(A/S1)^rho) + time1;
        sf = S1;
        l1x=(1/teehat)*((S1/A)^rho)*(tnptf-time1);
        l6x(j)=lx+l1x;
   end
   lifex(j)=tnptf;


%  **** PROOF TESTED FIBERS ****

   tptf = t_ramp;
   ssf = ldot1*tptf;

     if tptf<=time1
     l=(1/(teehat*(rho+1)))*((ldot1/A)^rho)*(tptf^(rho+1));
     else

l=(1/(teehat*(rho+1)))*((ldot1/A)^rho)*(time1^(rho+1));
     end
     l6(j)=l;


   if tptf>time1
       tptf = (tau-l)*(teehat*(A/S1)^rho) + time1;
       ssf = S1;

         if tptf<=time2
         l1=(1/teehat)*((S1/A)^rho)*(tptf-time1);
         else
         l1=(1/teehat)*((S1/A)^rho)*(time2-time1);
         end
       l6(j)=l+l1;



     if tptf>time2

       tptf=(((tau-l-l1)*(teehat*ldot2*(rho+1)/A)...
            +((S1/A)^(rho+1)))^(1/(rho+1))-(S1/A))...
            *(A/ldot2)+time2;
       ssf = ldot2*(tptf-time2)+S1;

         if tptf<=time3
         l2=(1/teehat)*((((ldot2*(tptf-time2)+S1)/A)^(rho+1)...
                 -((S1/A)^(rho+1)))*(A/(ldot2*(rho+1))));
         else
         l2=(1/teehat)*((((ldot2*(time3-time2)+S1)/A)^(rho+1)...
                 -((S1/A)^(rho+1)))*(A/(ldot2*(rho+1))));
         end
        l6(j)=l+l1+l2;
```

```
    if tptf>time3

tptf = (tau-l-l1-l2)*(teehat*(A/S2)^rho)+time3;
ssf = S2;

  if tptf<=time4
  l3=(1/teehat)*(((S2/A)^rho)*(tptf-time3));
  else
      l3=(1/teehat)*(((S2/A)^rho)*(time4-time3));
      end
 l6(j)=l+l1+l2+l3;


if tptf>time4
tptf=-(((tau-l-l1-l2-l3)*(teehat*(-ldot3)...
     *(rho+1)/A)+((S2/A)^(rho+1)))^(1/(rho+1))...
     -(S2/A))*(A/ldot3)+time4;
ssf = S2+ldot3*(tptf-time4);

  if tptf<=time5
  l4=-(1/teehat)*((((ldot3*(time4-tptf)+S2)/A)^(rho+1))...
    -((S2/A)^(rho+1)))*(A/(ldot3*(rho+1)));

  else

l4=-(1/teehat)*((((ldot3*(time4-time5)+S2)/A)^(rho+1))...
    -((S2/A)^(rho+1)))*(A/(ldot3*(rho+1)));

  end
l6(j)=l+l1+l2+l3+l4;


    if tptf>time5
    tptf =(tau-l-l1-l2-l3-l4)*(teehat*(A/S1)...
         ^rho) +time5;
       ssf= S1;
    life(j)=tptf;
    l5=(1/teehat)*((S1/A)^rho)*(tptf-time5);
    l6(j)=l+l1+l2+l3+l4+l5;


             end
  end
  end
  end
if tptf>time5
  ftnew(LL)=tptf;
  ftmin=min(ftnew);
```

```
          LL=LL+1;

        end


end

   tnpt(j)=tnptf;
   s(j) = sf;
   tpt(j)=tptf;
   ss(j) = ssf;


end

   tnpt=tnpt';
   s=s';
   tpt=tpt';
   ss=ss';
deltime(jj)=(ftmin-time2);
end
%
% Routine to develope histogram for no failure time.
%

%
sort(deltime);
number1=length(deltime);
tmax1=max(deltime);
tmax1=log10(tmax1);
tmin1=min(deltime);
tmin1=log10(tmin1);
dt1=(tmax1-tmin1)/10;
y1=zeros(11,1);
xt1=zeros(11,1);

for k=1:number1
   i=1;
   dtime=deltime(k);
   dtime=log10(dtime);
        for tim1=tmin1:dt1:tmax1

            tnext1=tim1+dt1;

               if dtime>=tim1
                 if dtime<tnext1
                 y1(i)=y1(i)+1;
                 xt1(i)=10^((tim1+tnext1)/2);
                 end
               end
            i=i+1;
```

```
    end

end

clg
semilogx(tnpt,s,'yX')
xlabel('log time (sec)'),ylabel('load (gm)'),grid
title('Non-Proof Tested Failure Times')
pause

clg
semilogx(tpt,ss,'rX')
xlabel('log time (sec)'),ylabel('load (gm)'),grid
title('Proof Tested Failure Times')
pause

clg
y1=y1./n;
semilogx(xt1,y1,'y+')
xlabel('log time (sec)'),grid
title('Post-Proof Test Safety Zone Histogram')


%  ***** SAVE DATA *****

% Histogram Data
save XT1.m xt1 -ascii
save Y1.m y1 -ascii

% Proof Test Data
save SS.m ss -ascii
save TPT.m tpt -ascii

% Non-Proof Test Data
save S.m s -ascii
save TNPT.m tnpt -ascii
format short e
```

B. PARAMETERS IN POST-PROOF TEST SIMULATION

A total of 2000 fiber strengths were simulated in each of 50 runs. A total of nine cases were looked at. For each case, the following parameters were used:
$\alpha=5$, $\beta=20$, L_1 = .8, L_2 = .8, L_3 = -.8, ρ = 40, teehat = 1
t_2 = 50000, dwell time = 1.

For run #1: S_1 = 7, proof load (dS) = 3
For run #2: S_1 = 7, proof load (dS) = 5
For run #3: S_1 = 7, proof load (dS) = 7
For run #4: S_1 = 10, proof load (dS) = 3
For run #5: S_1 = 10, proof load (dS) = 5
For run #6: S_1 = 10, proof load (dS) = 7
For run #7: S_1 = 13, proof load (dS) = 3
For run #8: S_1 = 13, proof load (dS) = 5
For run #9: S_1 = 13, proof load (dS) = 7

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7.	Joseph H. Woodward, LT, USN 812 Calle del Corte Albuquerque, NM 87110	2
8.	Gregory S. Morin, LT, USN 29 Wildwood Rd Gilford, NH 03246	1