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SPECTRUM FATIGUE LIFETIME AND RESIDUAL STRENGTH FOR FIBERGLASS LAMINATES

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and Livermore, California 94550 for the United States Department of Energy
under Contract DE-FC02-91ER75681

ABSTRACT

This report addresses the effects of spectrum loading on lifetime and residual strength of a typical fiberglass laminate configuration used in wind turbine blade construction. Over 1100 tests have been run on laboratory specimens under a variety of load sequences. Repeated block loading at two or more load levels, either tensile-tensile, compressive-compressive, or reversing, as well as more random standard spectra have been studied. Data have been obtained for residual strength at various stages of the lifetime. Several lifetime prediction theories have been applied to the results.

The repeated block loading data show lifetimes that are usually shorter than predicted by the most widely used linear damage accumulation theory, Miner’s sum. Actual lifetimes are in the range of one-tenth to one-fifth of predicted lifetime in many cases. Linear and nonlinear residual strength models tend to fit the data better than Miner’s sum, with the nonlinear providing a better fit of the two. Direct tests of residual strength at various fractions of the lifetime are consistent with the residual strength models. Load sequencing effects are found to be insignificant. The more a spectrum deviates from constant amplitude, the more sensitive predictions are to the damage law used. The nonlinear model provided improved correlation with test data for a modified standard wind turbine spectrum. When a single, relatively high load cycle was removed, all models provided similar, though somewhat non-conservative correlation with the experimental results. Predictions for the full spectrum, including tensile and compressive loads were non-conservative relative to the experimental data, but accurately captured the trend with varying maximum load. The nonlinear residual strength based prediction with a power law S-N curve extrapolation provided the best fit to the data in most cases. The selection of the constant amplitude fatigue regression model becomes important at the lower stress, higher cycle loading cases. For design purposes, a more conservative model, such as using a Miner’s Sum of 0.1 (suggested in the literature) may be necessary.

The residual strength models may provide a more accurate estimate of blade lifetime than Miner’s rule for some loads spectra. They have the added advantage of providing an estimate of current blade strength throughout the service life.

ACKNOWLEDGMENTS

This report is taken directly from the Doctoral thesis of Neil K. Wahl [1], by the same title, Department of Mechanical Engineering, Montana State University, August, 2001. The research was supported by Sandia National Laboratories through subcontracts AN-0412 and BC-7159, and the U.S. Department of Energy and the State of Montana under the EPSCoR Program, Contract DE-FC02-91ER75681.

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INTRODUCTION

The development of predictive design tools for the lifetime of fiberglass laminates has lagged that of metals [2-4] for a number of reasons, one of which is the anisotropic nature of the laminates. While metals have the single damage metric or parameter of crack size, composites have many more complicated failure modes. Failure of composites may include matrix cracking, delamination, fiber debonding, fiber pullout, fiber buckling, ply delamination, ply failure, and fiber fracture; a typical failure may involve a complex contribution of some or all these possible mechanisms. Although lifetime rules based upon nearly every laminate property have been proposed, many seem to have limited validity, with theoretical and actual lifetimes sometimes decades apart [5]. The more complicated models do not seem to yield better results than the linear damage accumulation law first proposed by M. A. Miner in the 1940's [4, 6, 7]. Despite this law’s shortcomings, it is used throughout the wind industry, for estimating laminate wind turbine blade lifetimes, e.g., Sandia National Laboratories’ computer code LIFE2 [8-10], as well as by many researchers in laminate fatigue [11-13].

Fatigue testing of fiberglass laminates typically involves the constant amplitude sinusoidal loading of a specimen until failure. Illustrated in Figure 1 are data, captured by use of a digital storage oscilloscope. The data are typical of load cycles used in constant amplitude fatigue testing. In the test, the cycle rate was 10 Hz, with maximum and minimum loads of 6.4 and 0.64 kN, respectively. Shown on the oscilloscope screen capture are both the demand and feedback signals from the test machine controller. The demand signal slightly leads the feedback signal. There is a slight amplitude deviation between the demand and feedback of approximately 1 percent in this example. The variation is a function of the laminate, test frequency, load levels and controller tuning.

Data such as found in References 13 and 14, which consist of the results of constant amplitude testing, are readily available. Unfortunately, constant amplitude testing and the Miner’s rule ignore any possibility of load interaction and load sequence effects, which may be particularly important for load spectra that are random in nature. Shown in Figures 2 and 3 are variable amplitude spectrum loading histories for wind turbine blades. Figure 2 is a portion of a European standard loading spectrum [15, 16]; note the single, relatively large cycle of higher stress that must be considered in any fatigue model. This European spectrum is a distillation of flap load data collected from near the root of the blades of nine wind turbines in Europe. A portion of the edge bending moment loading of a blade of a Micon 65/13 wind turbine in California is shown in Figure 3 [17]. This loading is typical of a variable amplitude loading spectrum that may be encountered in industry. An arbitrary time scale is shown, as the frequency can be set by the operator when applying these load histories in a laboratory testing program.

Researchers and wind energy industry authorities have spelled out a need for improved life estimating rules and for the study of variable amplitude or spectrum loading [5, 9, 19]. The goal of the research presented by this dissertation was to investigate improvements to lifetime

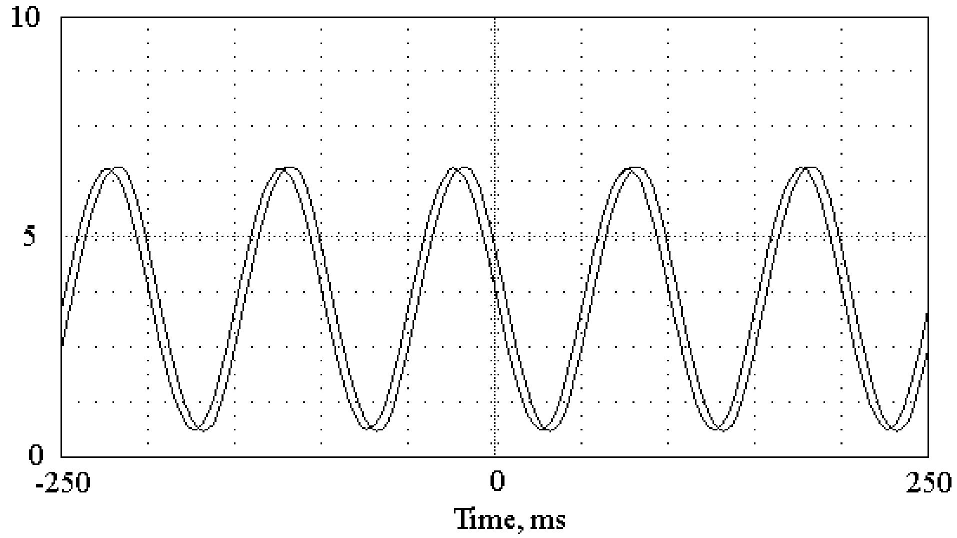


Figure 1.Constant Amplitude Load History.

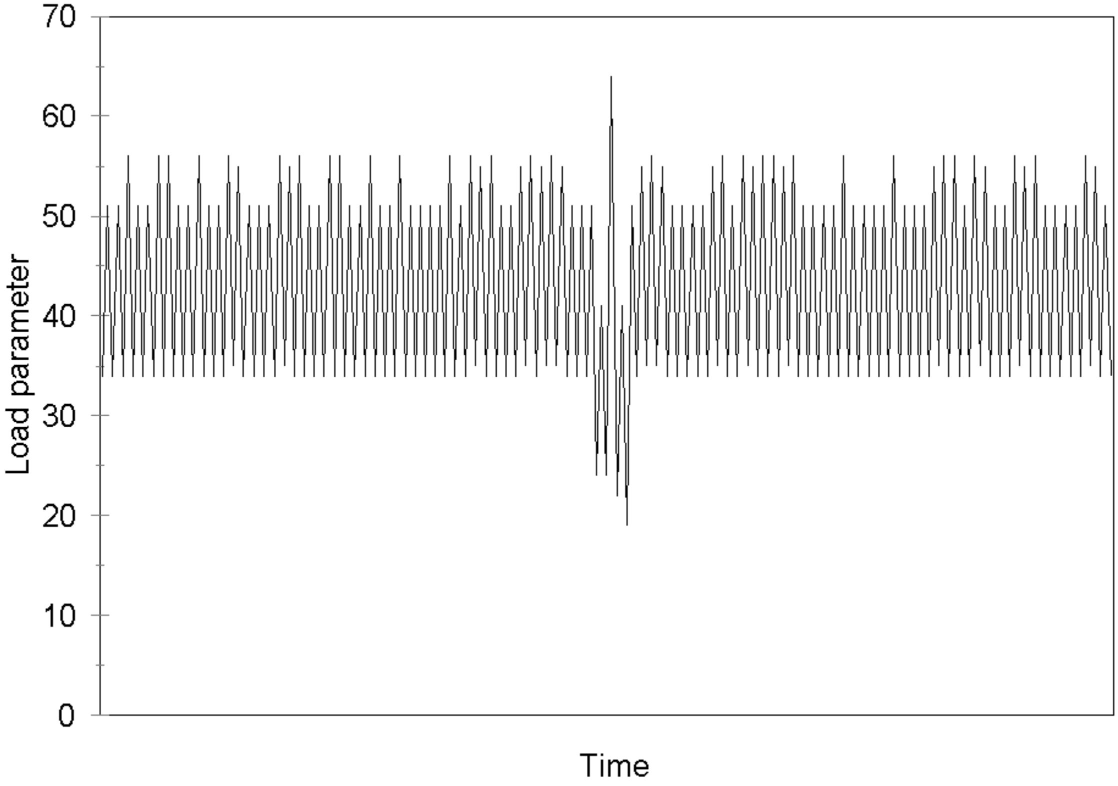


Figure 2. Portion of European Standard Variable Amplitude Fatigue Load History.

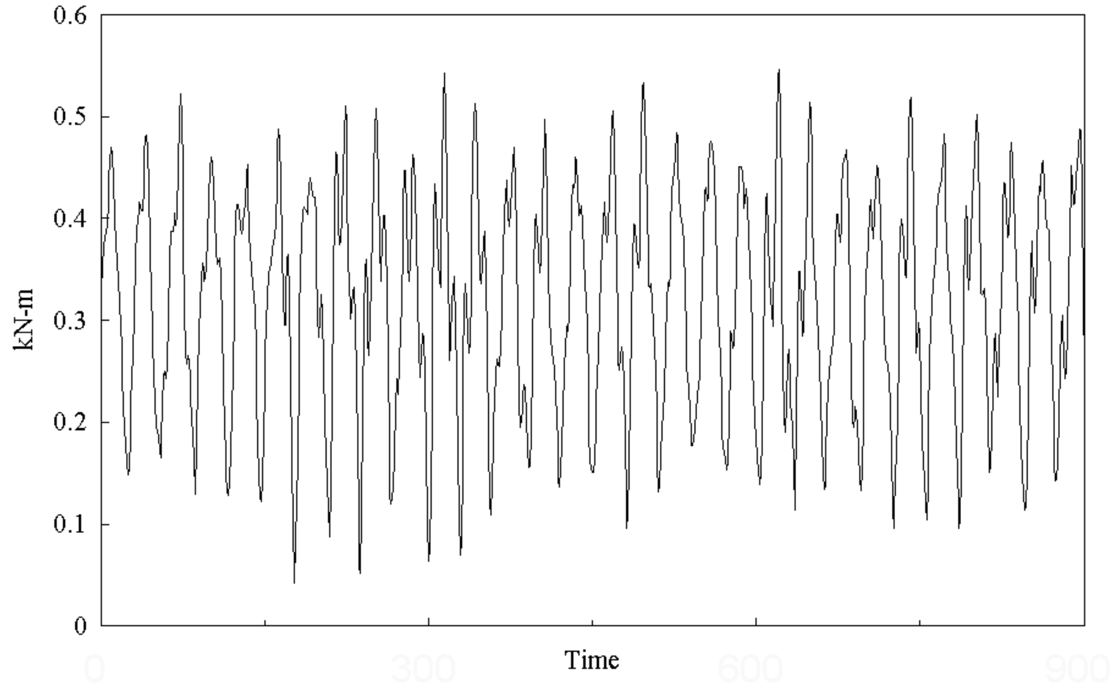


Figure 3. Edge Bending Moment Loading of a Micron 65/13 Turbine in California [17].

prediction rules for fiberglass laminates used in the construction of wind turbine blades. Any model that would be readily accepted must be easy to use, contain a minimum of parameters, and be accurate [20].

Very few researchers have undertaken an investigation of lifetime prediction models that started at the simplest of fatigue cases and logically progressed through an ever increasing complexity. Most research efforts can be characterized as a study of constant amplitude fatigue followed by the development of a lifetime prediction model, and, finally, an attempt to verify the model by analyzing the fatigue of specimens subjected to a two-level block loading spectrum, with the second block run to failure. Sendeckyj [20] and Bond [21] itemized a research program that would lead to the development of a rational life prediction model. The work, herein summarized, attempts to follow those guidelines [20]; namely,

1. establish an experimental program to investigate the damage process of the laminate
2. determine a valid damage measurement method (metric)
3. develop a life prediction rule based upon the established metric
4. experimentally validate the life prediction rule.

The experimental program should begin with constant amplitude fatigue testing and progress to block spectra fatigue testing [21].

FATIGUE OF MATERIALS

Fatigue is typically defined as the failure of a material due to repeated loading at levels below the ultimate strength. The general nature of fatigue for the two common materials, metals and fiberglass laminates, will be reviewed in this chapter along with some fundamentals of fatigue testing.

Background

Fatigue of materials subjected to cyclic loading (Figures 1, 2 and 3) is dependent upon not only the maximum stress level encountered, but also the range of the stresses applied. Generally, the greater the maximum stress, and the greater the range, greater damage is encountered. Although there are a variety of methods for describing each cycle of loading of a specimen, the method normally accepted for laminates is the maximum stress and R-value, R

$$R = \frac{\sigma_{min}}{\sigma_{max}} \tag{1}$$

where σ_{min} is the minimum stress level
σ_{max} is the maximum stress level.

Summarized in Figure 4 are the basic descriptions of the various cycle stress parameters.

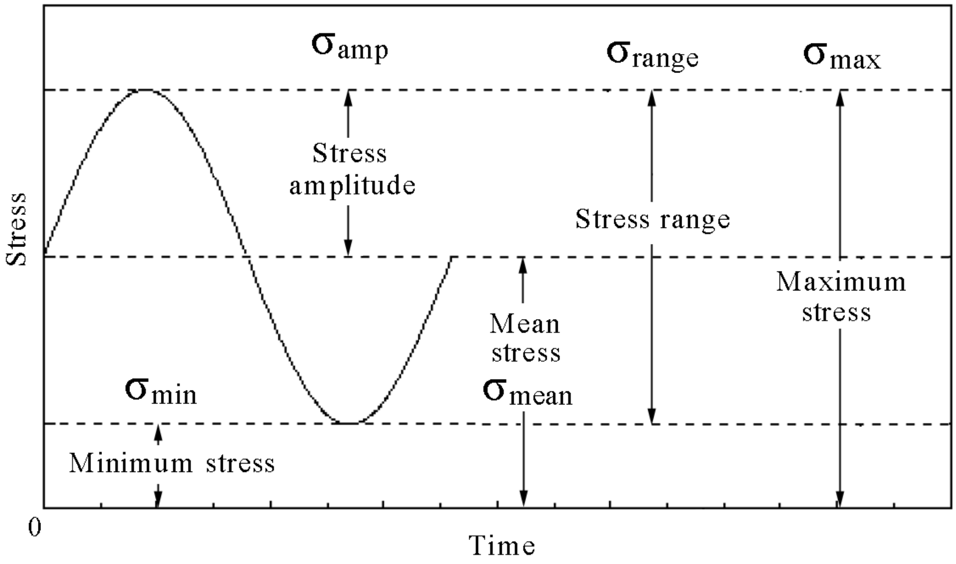


Figure 4. Cyclic Loading Test Parameters.

Displayed in Figure 5 are a grouping of typical R-values as well as an identification of the primary loading regimes.

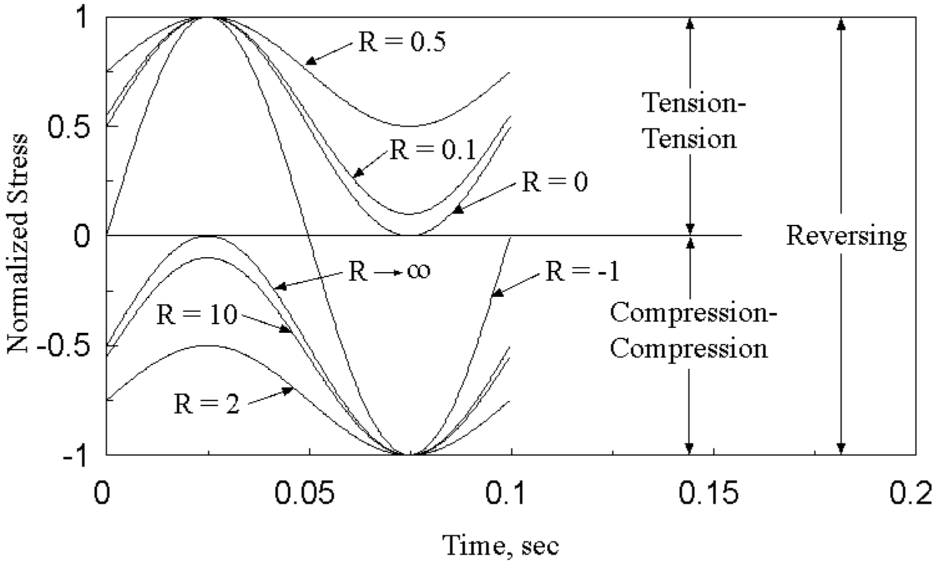


Figure 5. Load Regimes and R-Values.

Constant amplitude testing of a material at a constant R-value, but at a family of maximum stress levels is typically summarized in stress-cycle (S-N) diagrams. The information displayed on an S-N diagram is usually the maximum stress level as a function of the number of cycles to failure on a semi-log plot. Figure 6 [4] is a typical S-N diagram and for 7075-T6 aluminum.

Constant amplitude testing at a variety of R-values can be summarized within a Goodman diagram, see Figure 7, relating the alternating stress to the mean stress. Each set of tests at a constant R-value is represented by a straight line as defined in Equation 2. Small amplitude and consequently, longer tests are closer to the origin on any selected radial line of constant R-value.

$$\sigma_{alt} = \left[\frac{1 - R}{1 + R} \right] \sigma_{mean} \tag{2}$$

where σ_{alt} is the alternating stress value = σ_{amp}

R = R-value

σ_{mean} = mean stress level

A slope of zero represents the ultimate tensile strength test, while a slope of 180° represents an ultimate compressive strength test.

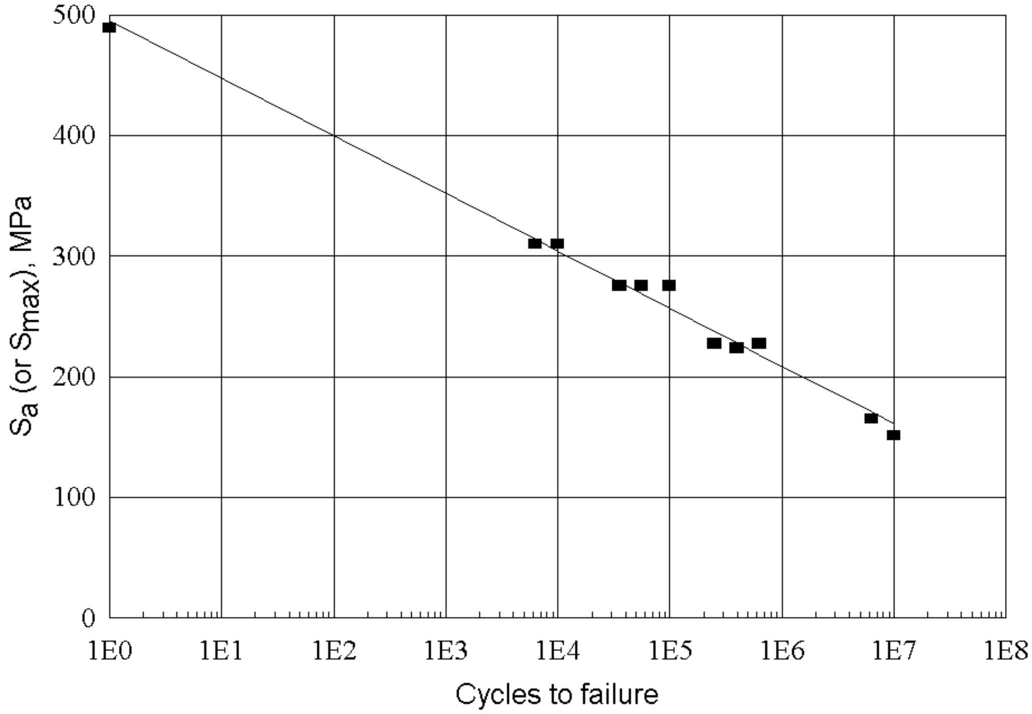


Figure 6. S-N Curve for 7075-T6 Aluminum Alloy, Fully Reversed (R-value = -1) Axial Loading [4].

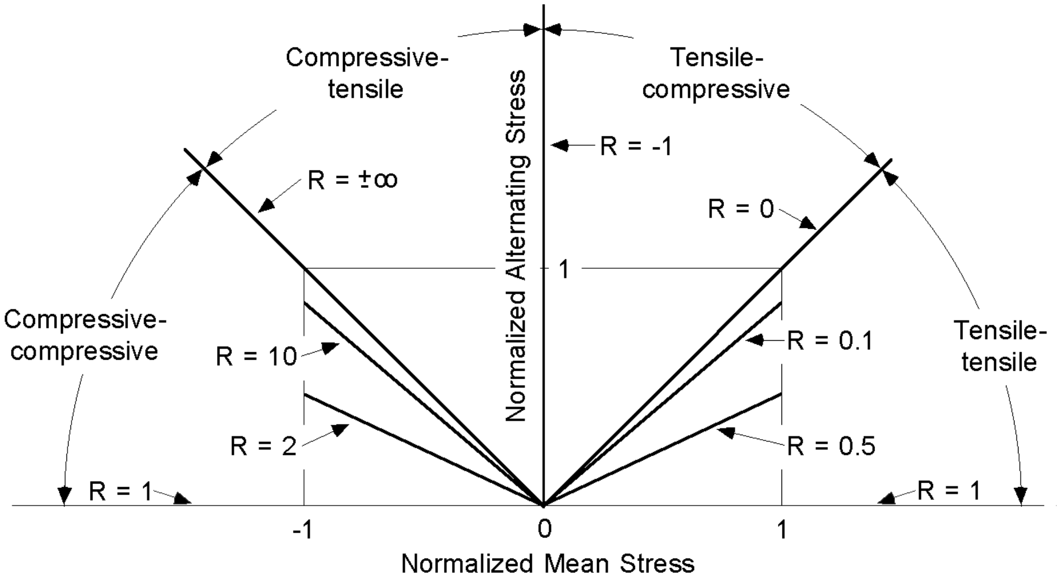


Figure 7. Goodman Diagram.

Historically, the first serious concern for fatigue failure in metals came with the expansion of the railway industry in the mid 19th century. Early investigations by Wöhler led to the summary of constant amplitude fatigue in diagrams relating stress and life (S-N diagrams). These diagrams can be considered a means for life prediction for metals subjected to constant amplitude loading. Estimates of S-N diagrams can be developed from fundamental material properties, thereby speeding the design process by minimizing laboratory fatigue testing. Other investigators, Gerber and Goodman [2], researched the effects of the mean and range of stresses upon lifetimes. For a given maximum stress level, the greater the stress range the greater the cyclic damage. Diagrams relating the mean and alternating stresses bear the names of these gentlemen.

Palmgren proposed [22] and Miner developed [6] the first cumulative damage rule in attempts to account for variable amplitude cyclic loading. Frequently, the “Miner’s rule” is called a linear model, relating to the linear addition of damage contributions of each cycle of loading. Each cycle is considered to contribute damage in the amount of the fractional amount of life expended at that cycle’s constant amplitude equivalent.

$$Miner's\ Sum = \sum_i \frac{n_i}{N_i} \tag{3}$$

where i is the cycle sequential index
n_i is the number of cycles at stress level σ_i
N_i is the number of constant amplitude cycles to failure at stress level σ_i

Miner’s work in aluminum revealed a wide variation in the predictive capability of this linear damage rule. The rule is incapable of accounting for any sequence effects for a variable amplitude load spectrum. Sequencing effects or load interactions such as work hardening and “over stressing” are not addressed by this rule [6]. Over stressing is the loading sequence of first applying high loads and then cycling the material to failure at lower loads.

Irwin can be considered the father of linear elastic fracture mechanics (LEFM) and fatigue crack growth lifetime predictions. During the last half of the 20th century, failure of aircraft and bridges due to crack growth led to the development and acceptance of fracture mechanics for lifetime predictions [2, 3, 23, 24].

It is generally understood and approximated that the crack growth rate is a function of the stress intensity factor as the Paris law [3, 23, 24].

$$\frac{da}{dN} = C\Delta K^{-m} \tag{4}$$

where a is the crack size

N is the number of cycles of loading
ΔK is the stress intensity factor range
C and m are constants for the material

This Equation is valid over a portion of the lifetime or crack growth history. The relationship fits the middle range of the overall S-shaped crack growth rate versus ΔK curve on a double logarithmic plot as shown in Figure 8 [26]. At the low stress intensity factors of region I, crack growth is extremely slow, leading to the postulate that crack growth does not occur below some threshold value, K_{th}. Region II covers a major portion of the crack growth and is modeled as the Paris law, Equation 4. Rapid crack growth occurs in region III, as the maximum stress intensity factor approaches some critical stress intensity factor K_c.

The stress intensity factor, K, is approximated with Equation 5 [3, 23, 24].

$$K = S_a \, Y\sqrt{\pi \, A} \tag{5}$$

where S_a is the applied stress
Y is a geometric factor
a is the crack length

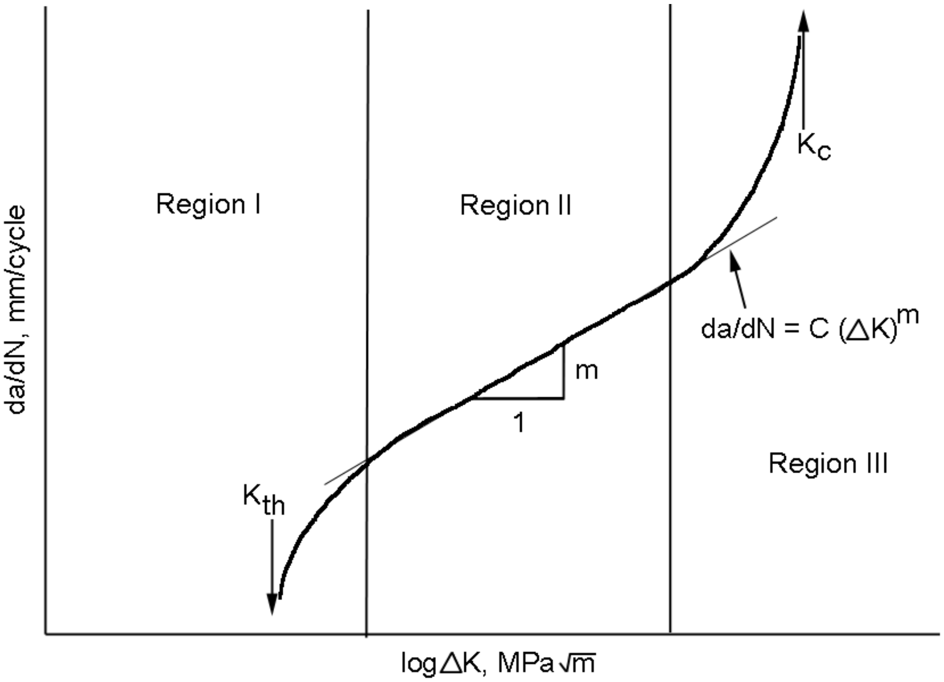


Figure 8. Stress Intensity Factor and Crack Growth Rate Trends.

Substitutions, rearrangement and integration of the above two Equations results in an expression relating the number of cycles required to grow a crack between two sizes (Y is taken as 1.0):

$$N = \frac{1}{C S_a^{m} \pi^{m/2}} \left(\frac{2}{-m+2} \right) a^{\frac{-m+2}{2}} \Bigg|_{a_i}^{a_d} \quad ,(m \neq 2) \tag{6}$$

where a_d is the minimum detectable crack size
a_i is some increased crack size
N represents the number of required cycles
S_a is the applied stress
C and m are constants for the material

Load sequencing effects can be important in the fatigue of metals. Crack growth in constant amplitude fatigue has been found to be slowed by a high load cycle or overload [23]. The type of overload has a great effect on the crack growth rate or retardation. Tensile overloads can retard crack growth whereas compressive overloads will offer little effect by themselves or will cause a reduction of the beneficial retardation of a prior tensile overload. The amount of retardation is dependent upon the size of the plastic zone created at the crack tip during a tensile high load cycle. Upon relaxation of the high load, the material in the plastic zone will be in compression. The following “normal” cycles must cause the crack to progress through this compressed zone before continuing at the normal rate.

Fiberglass Laminates

The damage metric of metals is chiefly that of crack growth, whereas for laminates there is no clear, dominant metric. Damage can be attributed to a variety of contributors, such as fiber breakage, matrix cracking, fiber debonding and pullout and delamination.

The laminate under consideration in this research was comprised of E-glass reinforcement and a thermoset matrix. Each of these constituents play roles in the strength and fatigue resistance of the laminate. The tensile properties for loading in the fiber direction are fiber dominated, while compressive properties are matrix dominated [25].

Laminate Fatigue Description

The following description of the progression of fatigue damage of laminates is summarized from References 25 and 26. Reifsnider [25] provided a detailed analysis of the progression of fatigue damage in laminates as shown in Figure 9. This analysis considers both tensile and compressive loads as well as a variety of laminate ply orientations. Upon initial tensile cyclic loading, at levels below the ultimate strength, matrix cracks in the off-axis plies occur first. This cracking will continue until a pattern or spacing of the matrix cracking becomes saturated. This spacing is dictated by the ability of the laminate to redistribute the loads to the material between cracks. This degree of damage has been termed a characteristic damage state, which also signals a transition from one stage of damage development to another.

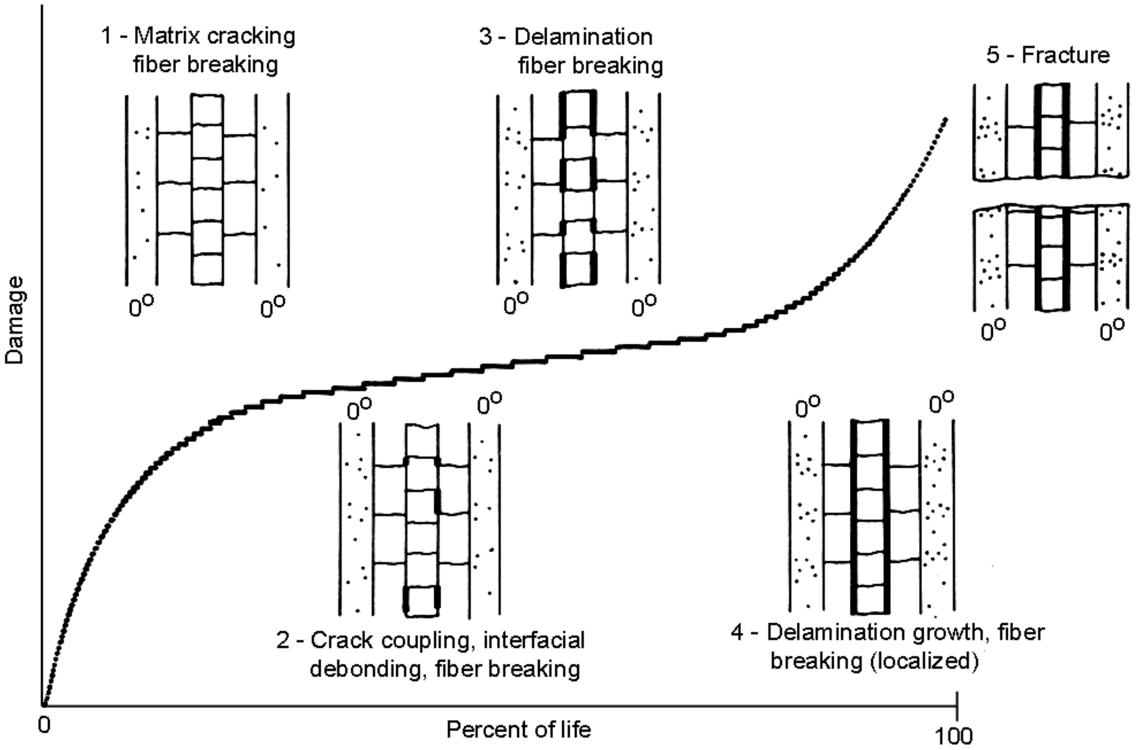


Figure 9. Schematic representation of the development of damage during the fatigue life of a composite laminate [25].

Upon continued cyclic loading, matrix cracking continues, but may develop in interlaminar areas and along axial fibers, causing a coalescing and interdependence of cracking, ultimately leading to localized delamination. Compressive excursions will promote this delamination process, not providing a damage retardation as was discussed for fatigue in metals.

Continued cycling will cause a spreading of and interaction of localized damage. Loads will be redistributed causing some fiber damage, breakage, debonding and delamination growth. With continuation of cycling, the load carrying capacity will be reduced to levels that can no longer support the applied load. The failure is sudden and catastrophic, with fiber breakage and pull out described as “brooming”.

The damage manifests itself in changes of bulk properties such as stiffness and residual or remaining strength of the laminate. After initiation of damage (analogous to loading metals at stresses that produce a stress intensity factor above its threshold) the damage accumulates rapidly at first and then accumulates more slowly. This acceleration and deceleration of damage is not consistent with the continual increase of damage accumulation (crack length) in metals. The damage accumulation in laminates is consistent with the initial rapid loss of stiffness and then a slowing of the stiffness reduction [27, 28]. This is also proposed in the lifetime prediction models for composite materials section as related to the loss of residual strength of laminates.

Fatigue Trends of Fiberglass Laminates

Constant amplitude fatigue testing of laminates is generally summarized in stress-cycle (S-N) diagrams and represented in models as either linear on semi-log (Equation 7) or log-log (Equation 8) plots for exponential or power law trends, respectively.

$$\frac{\sigma}{\sigma_0} = C_1 - b \log(N) \tag{7}$$

$$\frac{\sigma}{\sigma_0} = C_2 N^{-\frac{1}{m}} \tag{8}$$

where σ is the maximum applied stress
σ_0 the ultimate strength
N the number of cycles to failure
C_1, C_2, b and m are regression parameters

Rearrangement of Equations 7 and 8 to solve for N, led to Equations 9 and 10. Equation 9 is exponential in form, while Equation 10 is of the power law form.

$$N = 10^A \;, \quad where \quad A = \left[\frac{C_1 - \frac{\sigma}{\sigma_0}}{b} \right] \tag{9}$$

$$N = \left[\frac{\sigma}{C_2 \, \sigma_0} \right]^{-m} \tag{10}$$

Typical S-N curves for these fatigue regression analyses are shown in Figure 10.

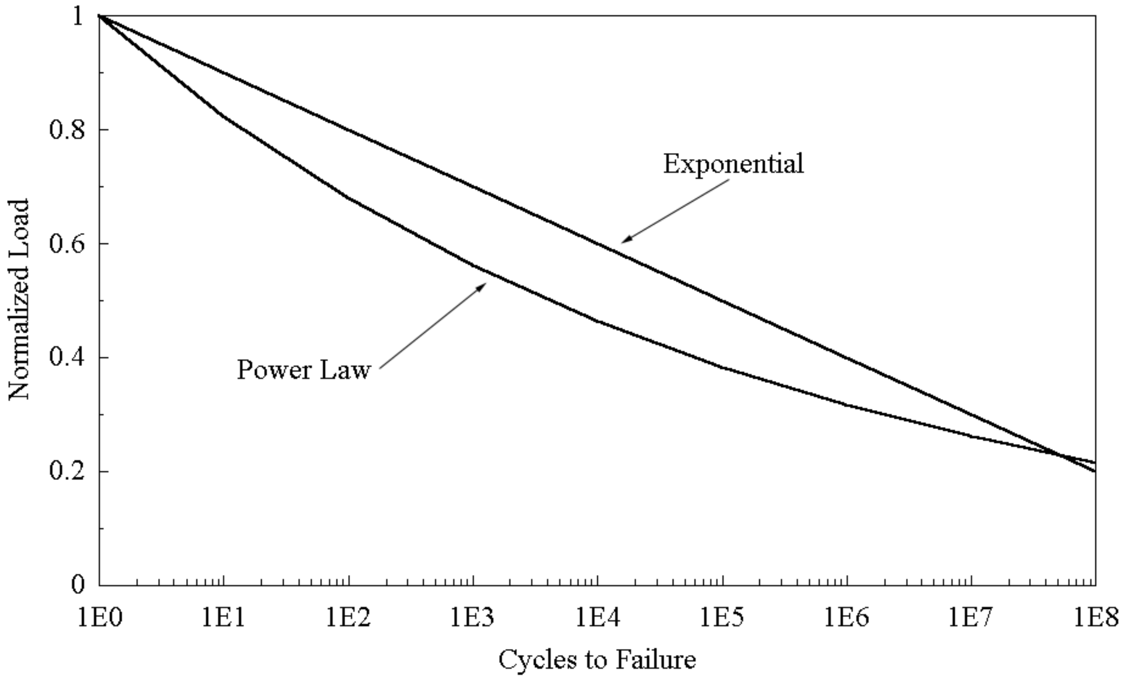


Figure 10. Comparison of Exponential and Power Law Constant Amplitude Laminate Fatigue Trends on Semi-Log Plot.

Much of the early work used exponential fits and semi-log plots, with the power law representation and log-log plots becoming popular with the advent of high cycle testing. Questions have arisen as to which is the better fatigue model (regression Equation) for use in lifetime prediction methods involving extrapolation to higher cycles [5, 10, 29-34]. The selection of the “best” fit may be the cause of a shift in the failure prediction at some fraction of the laminate’s life [35]. This seems somewhat subject to the material, type of loading and the fraction of life expended.

A general rule has been promoted for quick comparison of the fatigue sensitivity of various laminates comprised of 0^o and off axis plies. The stress or strain normalized slope, b, of the exponential regression has frequently been touted as 0.1 (10 percent per decade) for “good” fiberglass laminates in tension (R = 0.1), while a slope of 0.14 has been considered a “poor” material response [14, 36]. The general trend for the better laminates in compression (R = 10) is 0.07 (7 percent per decade), while the poorer laminates follow a fatigue trend of 0.11 (11 percent per decade) [36]. Reversing load (R = -1) fatigue response ranges from 0.12 to 0.18 (12 to 18 percent per decade). These fatigue trends are summarized in Figure 11.

Sutherland and Mandell [10] compiled a Goodman diagram, Figure 12, based upon the data of Reference 14. Note the asymmetry, relating to the differences in the tensile and compressive fatigue properties.

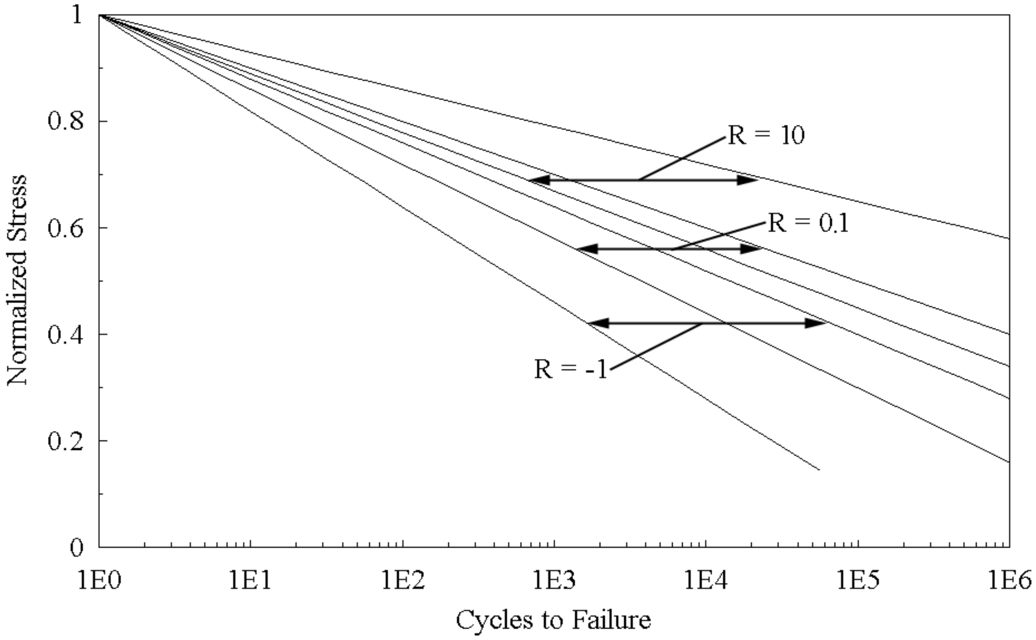


Figure 11. Laminate Fatigue Trends for Tensile, Compressive and Reversing Constant Amplitude Loads.

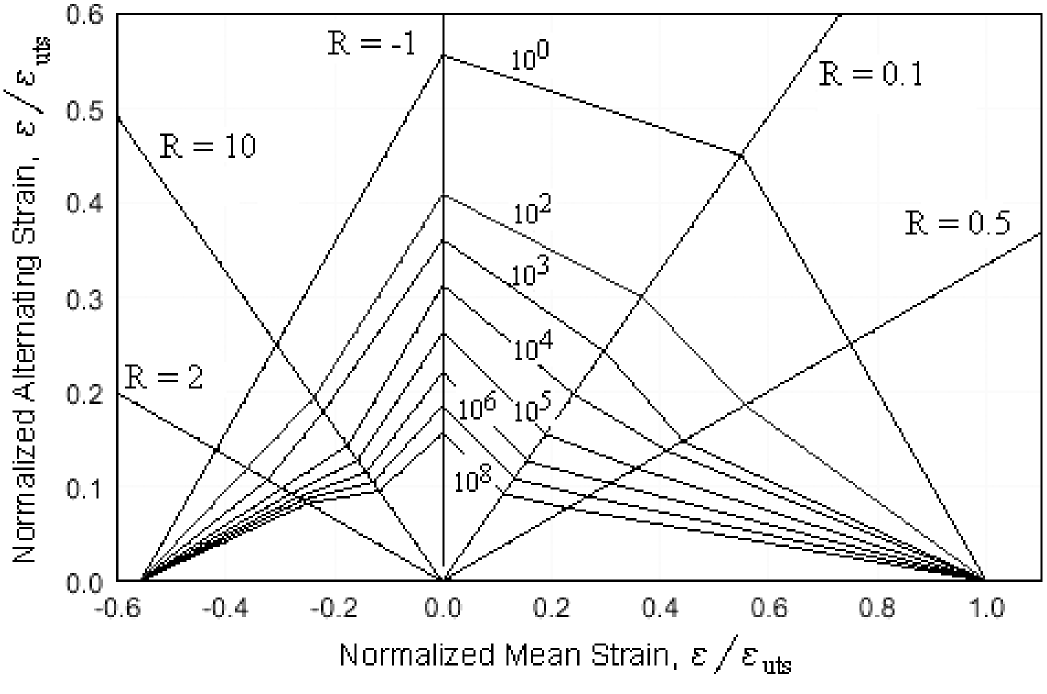


Figure 12. Normalized Goodman Diagram for Fiberglass Laminates Based on the MSU/DOE Data Base [10].

The fatigue sensitivity of unidirectional laminates does vary with fiber volume fraction, with the increase in fiber volume fraction resulting in increased magnitudes for the exponential regression parameter b. This is ostensibly due to the increased likelihood of fiber-to-fiber contact damage with the increased fiber volume. The fiber volume range summarized in Reference 36 was from 0.25 to approximately 0.62.

The effect of the content of 0^{o} plies of the laminate is summarized in Table 1 [14, 36]. The tensile fatigue trend is poorer in the laminates containing combinations of 0^{o} and $\pm 45^{o}$ plies and improves at the extremes of contents of these orientations. The compressive fatigue trend improves with greater 0^{o} ply content.

Table 1. Summary of Ply Orientation Effect on Fatigue Trends

Percent 0^{o} Plies	V_F	b, R = 10	b, R = 0.1
0, ($\pm 45^{o}$ only)	0.25 - 0.54	0.106	0.113
16	0.33 - 0.47	0.114	0.116
24	0.36 - 0.48	0.115	0.128
28	0.32 - 0.48	0.088	0.124
39	0.32 - 0.49	0.095	0.128
50	0.31 - 0.51	0.089	0.128
55-63	0.39 - 0.45	-	0.121
69-85	0.30 - 0.62	0.072	0.118
100 (0^{o} only)	0.30 - 0.59	0.073	0.111

The laminate studied in this research will be compared to the above laminate fatigue trends in constant amplitude fatigue testing and results section.

LIFETIME PREDICTION MODELS FOR COMPOSITE MATERIALS

Lifetime prediction models for laminates have been developed from the basis of nearly every conceivable property of the materials. Engineering mechanical properties such as stiffness and/or compliance [37-39], natural frequency [40], damping [40, 41], and residual strength [42-48] as well as micromechanical properties such as crack density [25], fiber-matrix debonding and pullout, and delamination [49] have been applied towards development of lifetime prediction models. Other models are based upon properties determined by simple fatigue tests of laminates and more evolved statistical analyses [42] of the material. Some researchers have applied linear elastic fracture mechanics, a method considered appropriate for isotropic materials such as metals, to the analysis of fatigue in composites. Regardless of the efforts expended upon the development of reliable models, and of the model's complexity, most researchers still compare the results of their work to the simple, linear model proposed by Miner [6]. The leap from the theoretical, advanced models to their practical use seems to be daunting. Computer codes that have been developed for the fatigue lifetime analysis for wind turbine blade design still use the first model, Miner's linear damage rule [8, 9, 42, 50], and have not applied the newer, and reportedly more reliable models. Practicing engineers prefer simple, easy to apply models, for their use in the design of components.

Miner's Linear Damage Rule

The early work on aluminum by Miner [6] resulted in a simple linear damage accumulation rule that was based upon constant amplitude fatigue test results. The basis of this rule is that the damage contribution of each load level is equal to its cycle ratio, which is the number of cycles experienced at that load level divided by the number of constant amplitude cycles to failure at that same load level. The damage contributions of each load level are algebraically added to allow determining an overall damage level. Symbolically, Miner's Sum can be represented as

$$D = \sum Cycle\ Ratios = \sum_i \frac{n_i}{N_i} \tag{11}$$

where D is a quantified damage accumulation parameter previously termed Miner's sum in Equation 3

i is the indexing parameter related to the number of different load levels

n_i is the number of cycles experienced at a σ_i maximum stress level

N_i is the number of constant amplitude cycles to failure at the stress level σ_i.

Typically, failure is taken to occur when D reaches unity, as originally proposed by Miner. For future reference and comparison to other lifetime prediction models, D_R is defined as the residual Miner's sum.

$$D_R = 1 - D \tag{12}$$

Miner’s original work with aluminum exhibited a range of values for D from 0.61 to 1.49, but with an average of 1.0 and a standard deviation of 0.25. Miner reported that his model did not include any provisions to account for the possibility of load interactions such as related to work hardening. The Miner’s rule has limitations in that it does not account for sequencing effects. The latter is sometimes referred to as a “sudden death behavior,” such as reaching K_c in the metals crack growth example.

Several researchers have proposed modifications to Miner’s rule to coax the damage parameter, D, closer to unity. Performing a square root, or for that matter any other root, forces the damage parameter closer to unity [13, 21, 42, 51]. Others merely acknowledge that the damage parameter may not be unity, and propose values other than one, such as 0.1 [50]. Any superiority of these modifications is often due to fitting of model constants to particular experimental data [4].

Graphically, Miner’s rule can be viewed as shown in Figure 13. The straight line relationship represents the Miner’s original linear rule, whereas the line lying below represents a prediction based upon applying a square root to the linear rule. The upper line represents the prediction should an exponent greater than one be applied.

This model has been tested by application of a two stress level spectrum of loads [11, 43]. The first set of cycles at a constant stress level constitutes a loading block. The second block of cycles at a second stress level was run to specimen failure. Empirical results for testing of fiberglass laminate (13 plies of 0^o and 90^o oriented E-glass fibers in an epoxy matrix) indicated a range of 0.29 to 1.62 for Miner’s sum [43]. The general observation was that for a block of high amplitude cycles followed by a block of low amplitude cycles would result in Miner’s sums greater than one. The opposite sequencing of a low amplitude block followed by a high amplitude block resulted in Miner’s sum less than one.

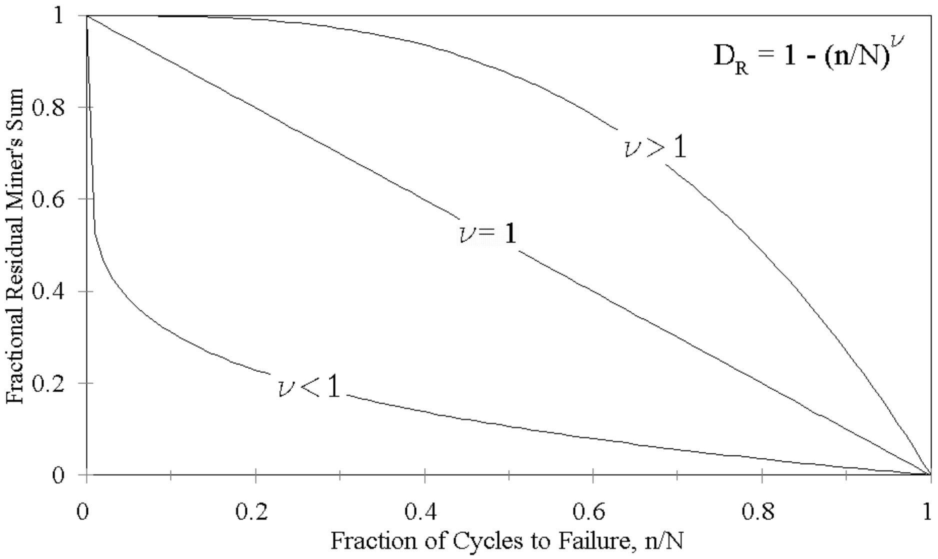


Figure 13. Effect of Exponent on Residual Miner's Sum Model (Constant Amplitude Fatigue).

Residual Strength Based Models

A concept of a material's progressive loss of strength during fatigue has led several researchers to investigate models with this basis [11, 20, 40, 43-48]. Broutman and Sahu [43] were one of the earliest to develop a model founded upon residual strength changes during fatigue. Their model was based upon a linear loss of strength with cycles of fatigue, as represented by:

$$\sigma_R = \sigma_0 + \frac{\sigma_i - \sigma_0}{N} n \tag{13}$$

where σ_R is the residual strength
σ_i is the maximum applied stress level
σ_0 is the static strength of the specimen
N is the number of constant amplitude cycles to failure at the stress level of σ_i
n is the number of cycles experienced at stress level σ_i

Broutman and Sahu [43] reported the residual strength lifetime prediction rule also satisfies the sequencing effects of high/low and low/high blocks of constant amplitude cycles. Spectra of a high amplitude block followed by a low amplitude block exhibited Miner's sums greater than one if the second block is run to failure. The opposite spectrum of a low followed by a high amplitude block yielded Miner's sums less than one.

Many investigators of residual strength and/or residual stiffness have argued that the residual strength is not a linear function of the number of cycles, but rather non-linear [11, 20, 44-46, 48]. This prompted a modification of the residual strength model to include non-linear possibilities:

$$\sigma_R = \sigma_0 + \left[\sigma_i - \sigma_0\right]\left[\frac{n}{N}\right]^{\nu} \tag{14}$$

where the parameter, ν, is termed the strength degradation parameter [44-46]. Strength degradation parameters greater than one define laminates that exhibit little loss of strength throughout most of their life and suffer a sudden failure at the end of life. Parameters less than one represent laminates that suffer the greater damage in their early life. A value of unity for ν reduces Equation 14 to the linear model of Equation 13.

The general shape of the residual strength curve, Figure 14, is uncertain. Upon considering a simple link between residual stiffness and residual strength, researchers have shown all possible ranges of the strength degradation parameter. This variation leads one to consider that the strength degradation parameter is a material property (possibly dependant on loading) and hence variable from laminate to laminate.

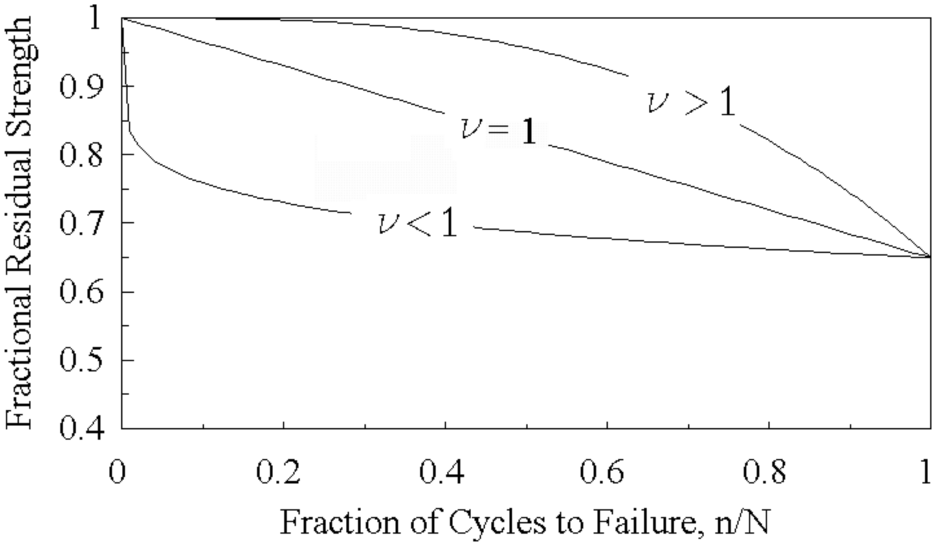


Figure 14. Effect of Exponent on Residual Strength Model (Constant Amplitude Fatigue).

Residual Stiffness Based Models

Another proposed model, similar to the residual strength model, is one based upon the change in stiffness, E, of a material undergoing fatigue [20, 37-39, 47, 52]. The residual stiffness prediction model represented by Equation 15 was proposed by Yang, et. al. [37] and is similar to the nonlinear residual strength model proposed by Schaff and Davidson [44-46]

$$E(n) = E(0) - \left[E(0) - E(n_k)\right]\left[\frac{n}{n_k}\right]^{\nu(k)} \qquad (15)$$

where E(n) and E(n_k) are the stiffnesses at cycles n and n_k respectively
E(0) is the initial stiffness
ν(k) is the fitting parameter.

The fitting parameter is considered to be a function of the applied stress level and perhaps even the number of cycles experienced. Experimental results for a graphite laminate of $[90/\pm45/0]_s$ layup were E(0) = 53.8 GPa, E(10,000) = 42 GPa, and ν(10,000) = 0.162 (dimensionless). These data were used to generate a graphical representation, Figure 15, of the change in the normalized stiffness over a normalized life.

Note the similarities of the graphs, Figures 14 and 15. The nonlinear residual strength model based upon a strength degradation parameter less than one presents a similar trend as the results of residual stiffness testing by Yang, et. al. [37] and Bach [38].

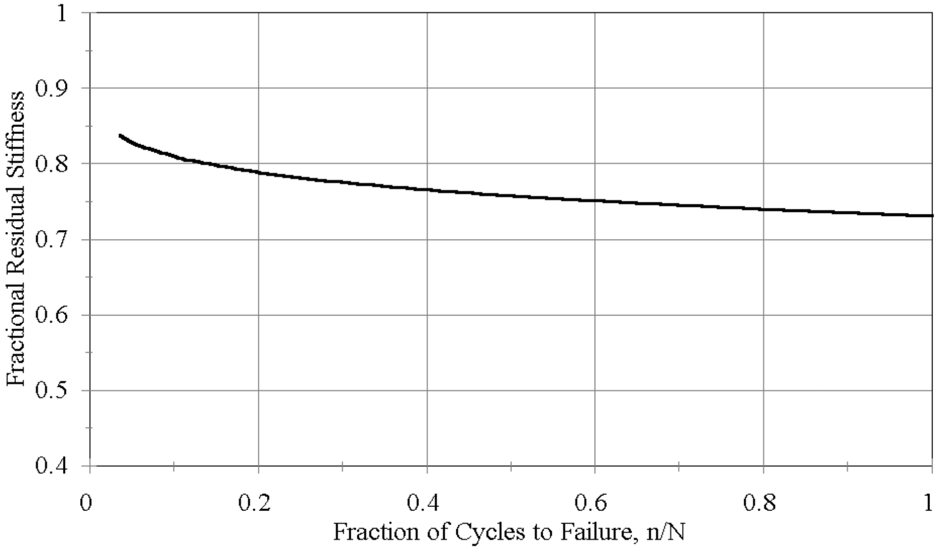


Figure 15. Laminate Residual Stiffness Experimental Trend (Constant Amplitude Fatigue, Carbon/Epoxy).

EXPERIMENTAL PROGRAM

A laboratory test program was developed in attempts to ensure the performance of meaningful fatigue tests. This program included the selection of a typical wind turbine blade fiberglass laminate, design of test specimens, test of laboratory equipment capability, and the execution of planned fatigue tests. The underlying goal was to first perform constant amplitude tests that could be compared with the results of other investigators and then methodically increase the complexity of the loading spectrum.

Investigation of variable amplitude fatigue, including that of two-level block loading load levels can be hampered by the scatter of the testing results. The scatter in constant amplitude fatigue data can be due to testing techniques, specimen preparation, variation in the material itself and the variability of fatigue mechanisms. With large scatter of data, the fatigue contribution of each load level in multi-load level testing becomes indistinguishable. Effects of several of these contributing factors can be minimized with proper design of test procedures and fabrication techniques.

Laminate Selection

The choice of the fiberglass laminate was to be one that would be typical of those used in wind turbine blade construction and one that would yield meaningful fatigue test results. The laminate materials and configuration or lay-up can have an effect on the statistical results of fatigue testing. Three different laminates were considered for testing; DD5, DD11 and DD16. The laminate designations are described in References 14 and 36 and in Table 2.

Table 2. Fiberglass Laminates

Material	Percent Fiber Volume	Ply Configuration	Matrix	Fabric Description
DD5	34	$[0/\pm45/0]_S$	P	0's - D155 45's - DB120
DD11	30	$[0/\pm45/0]_S$	P	0's - A130 45's - DB120
DD16	39	$[90/0/\pm45/0]_S$	P	0's & 90's - D155 45's - DB120
P - ortho polyester matrix, CoRezyn 63-AX-051 by Interplastics Corp. A130, D155 & DB120 - Owens Corning Fabrics				

Since this research was to consider spectrum loading effects on the fatigue life of fiberglass laminates, the statistical scatter of constant amplitude load testing was to be minimized. A related factor, the tendency of some coupons to fail near the grip, was also to be minimized under various loading conditions; the addition of 90° outside plies helped in this respect. Of the three laminates listed in Table 2, upon testing, the DD16 was chosen to be best suited for variable amplitude testing. Summarized in Figure 16 are preliminary constant amplitude fatigue test results for the material DD11. Note the high scatter in the life for the material when loaded to a maximum stress level of slightly greater than 400 MPa. The life for the material when subjected to fatigue at a stress level of 414 MPa was indistinguishable from that at the higher stress level of 475 MPa. The nearly two decades of scatter in the cycles to failure at the 414 MPa load level were deemed unacceptable from a practical standpoint, in trying to discriminate governing cumulative damage effects, and would have been undoubtedly even greater for lower stress tests. Similar, but not as pronounced results were also observed for test results of the DD5 material fatigue. In retrospect, the scatter has since been found to also depend on the variations in the particular reinforcing fabric [36].

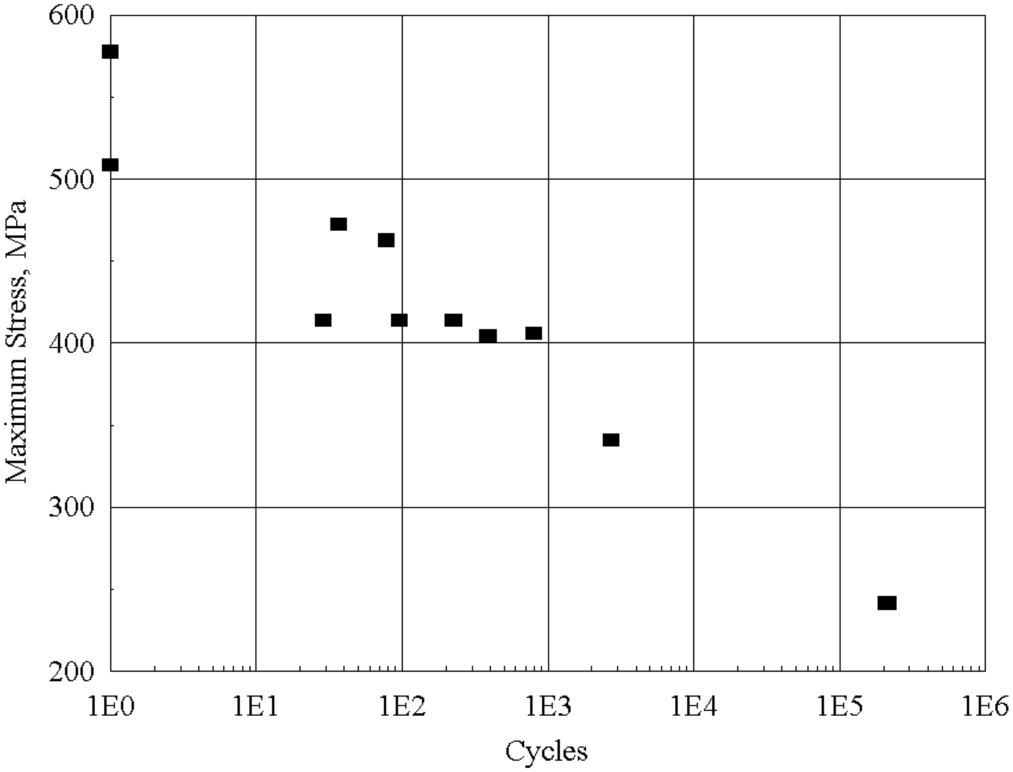


Figure 16. DD11 Constant Amplitude Fatigue, Preliminary Tests for Scatter, R = 0.1.

The material that produced acceptable scatter results was termed DD16 in the database of Reference 14. DD16 was comprised of Owens Corning D155 (stitched unidirectional) and DB120 (stitched ± 45°) fabrics in a $[90/0/\pm45/0]_S$ lay-up for a total of ten plies and eight layers of fabric. The

90° plies on the outside were thought to produce more reliable gage-section failures, as noted earlier. Photographs of the fabrics are shown in Figure 17. Plates of this material were fabricated by a resin transfer molding (RTM) process with Interplastics Corporation CoRezyn 63-AX-051 ortho polyester matrix to an average fiber volume of 0.36. Details can be found in References 14 and 36.

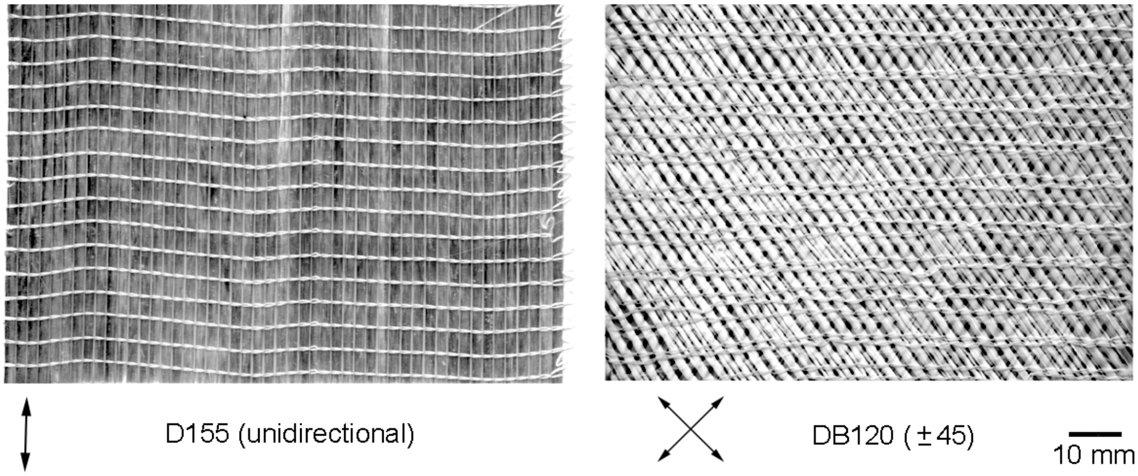


Figure 17. DD16 Laminate Dry Fabrics.

Coupon Design

Coupons were designed for the type of load testing to be fulfilled, whether for tensile-tensile (T-T), compressive-compressive (C-C), or reverse loading. The location and mode of failure was the factor used to determine the acceptability of the specimen design. The failure mode was to be attributed to the fatigue loading, and not to other factors such as thermal degradation, elastic buckling or gripping effects. Similarly, the location of the failure should be in the gage section as opposed to in or adjacent to the grips. The long history of test coupon geometry development for various fiberglass materials can be found in References 14 and 36.

Tension-Tension Coupons

Tensile-tensile specimen blanks were rectangular in shape, typically 12.7 mm wide by 4 mm thick and 64 to 75 mm long. These blanks were then individually machined to a dog-bone style with a pin router, clamping jig, and master pattern as shown in Figure 18. The profile of each edge was machined sequentially. Machined surfaces were then cleaned with sanding screen to remove any fiber "burrs". Sanding screen was also used to roughen the grip areas in preparation for the addition of tab material. G10 fiberglass tab material, manufactured by International Paper, Inc., was attached to facilitate distribution of testing machine gripping forces. The tabs were 1.6 mm thick with length and width varying dependent upon the test type, as shown in Figure 19. Attempts to perform tensile tests without tabs were not successful, due to laminate failure in the grips of the testing machine. Specimens with straight sides, with or without tabs, were also deemed not acceptable; failures occurred in the grips.

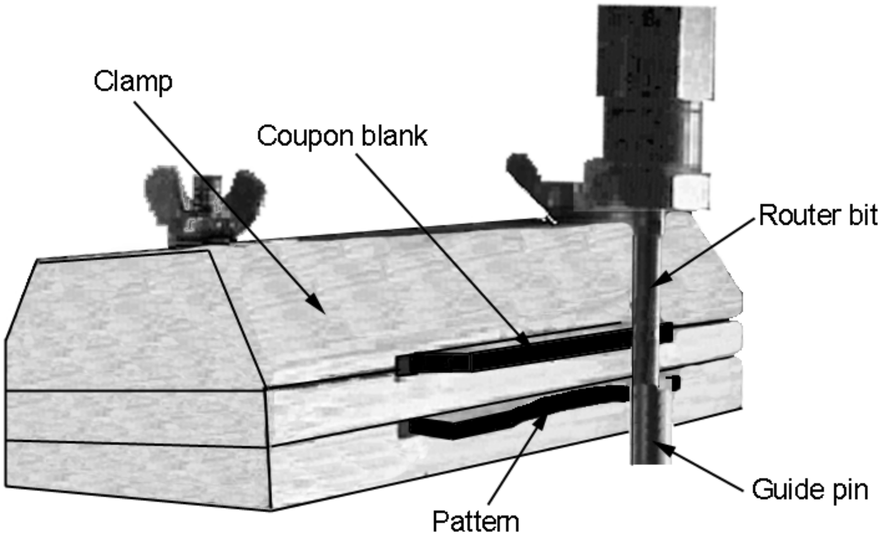
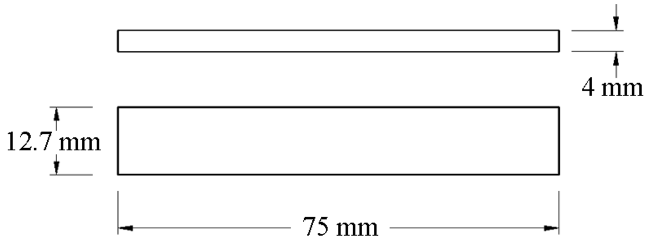


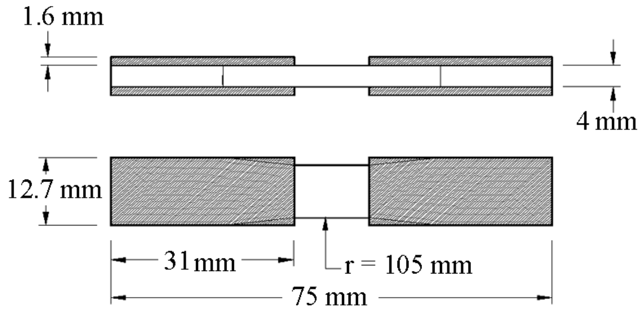
Figure 18. Pin Router.

Specimens with a gage section and tabs, Figure 19, were tested and found to be a successful coupon design. Typical examples of fatigue failures of these tensile specimen are shown in Figure 20. Failures occurred in the gage section and were typical of laminate tensile fatigue failures; the matrix material was severely fractured, fibers were pulled out, broken and "brooming" at the failure. This final design for a tensile test specimen is similar to that for metal-matrix specimen as per ASTM Standard D 3552, rather than the ASTM Standard D 3039 for polymeric-matrix specimens [53].

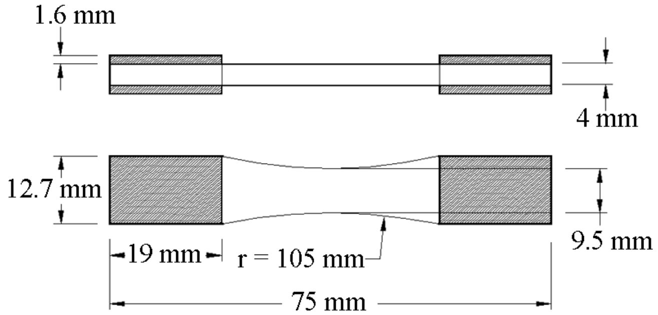
Typical failures are shown in Figure 20. Coupon number 555 was a tensile fatigue test performed at an R-value of 0.1 and a constant amplitude maximum stress level of 207 MPa. Coupon 716 was tested with an R-value of 0.1, but under a variable amplitude loading spectrum and with a maximum stress of 245 MPa. Coupon 773 was subjected to a variable amplitude loading spectrum, but with R-values of both 0.1 and 0.5 and a maximum stress of 245 MPa. The bottom coupon, number 774, was subjected to an ultimate tensile test. All coupons displayed the severe fracturing of the matrix, some even to the point of total wasting of the matrix around the 45 degree plies. All examples also exhibit the "brooming" of the fibers that occurred with this explosive type of failure.



Compression test coupon



Reversing test coupon



Tension test coupon

Figure 19. Test Coupon Configurations.

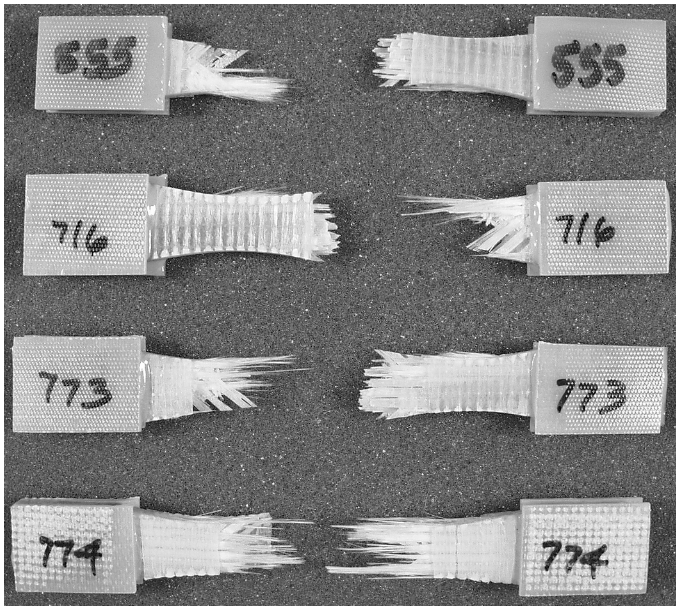


Figure 20. Tensile Coupon Failure Examples.

Compression-Compression Coupons

The specimens designed for the tensile fatigue testing were first considered for compression testing. Unfortunately, buckling was evident due to slight misalignment caused by the variation in tab material thicknesses and also due to the length of the gage section. A workable compression specimen was a simple rectangularly shaped laminate without any tab material. The gage section was held to 12.7 mm by the grips, to preclude buckling. The overall dimensions were the same as those of the tensile specimen blanks. The failure mode of the compression specimen tests was matrix fracture and destruction, resultant fiber debonding, delamination and crushing or buckling of the fibers, Figure 21. Final crushing was relatively symmetrical on each face in the thickness direction, indicating an absence of elastic buckling or misalignment [14, 36].

Typical compression failures are shown in Figure 21. Coupon number 860 was subjected to constant amplitude loading spectrum at an R-value of 10 and with a minimum (maximum negative) stress of -207 MPa. Number 915 was subjected to a constant amplitude loading spectrum at an R-value of 2 and a minimum stress of -325 MPa. The bottom example in Figure 21 was subjected to a two-level block loading spectrum with minimum stress levels of -325 and -207 MPa and at an R-value of 10. Each of these examples exhibited the failure mode of matrix cracking, delamination, and final buckling of the fibers due to loss of lateral support with the disintegration of the matrix material.

Figure 22 depicts the delamination that occurred during the compressive cyclic loading of coupons 906, 908 and 893 top to bottom respectively. All three tests were performed at an R-value of 10, with tests 906 and 908 at a maximum compressive stress of 245 MPa and test 898 at 275 MPa. The lower stress tests were terminated at approximately ten million cycles and were considered run-out, or cases that could run for a longer period of time. Coupon 893 was terminated at roughly 60,000 cycles as an example of delamination response. All three coupons display signs of delamination growth from the edges. Had the cycling continued until failure, undoubtedly, the delamination would have progressed from each side, eventually joining. The weakened laminate would have had reduced buckling resistance and failed similarly to the examples shown in Figure 21. This mode of compressive failure is common in composites with off-axis plies. While the machined edges may lead to some decrease in fatigue lifetime compared with material having the absence of edges, the constant amplitude compressive fatigue S-N trend found here is similar to that for materials without off-axis plies, such as unidirectional D155 fabric composites [14]. Thus, the edge delamination is not expected to significantly affect the application of these results to other geometries.

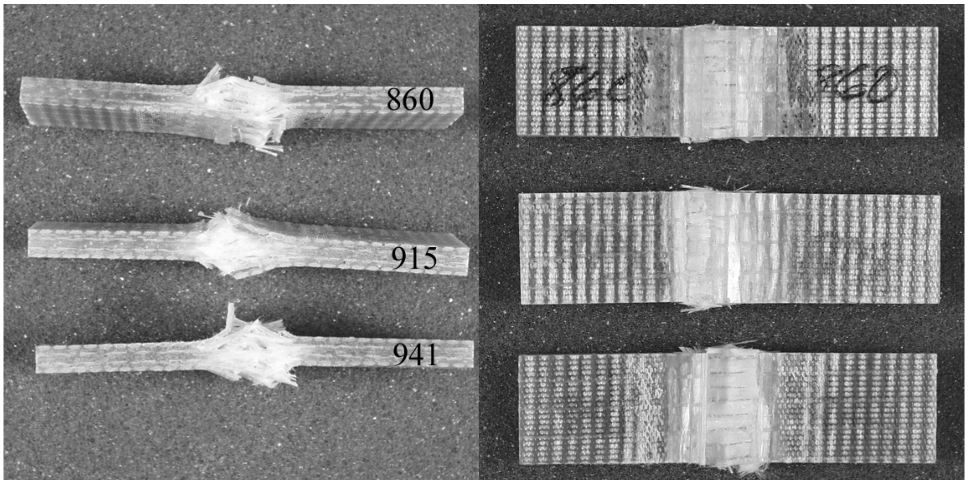


Figure 21. Compressive Coupon Failure Examples.

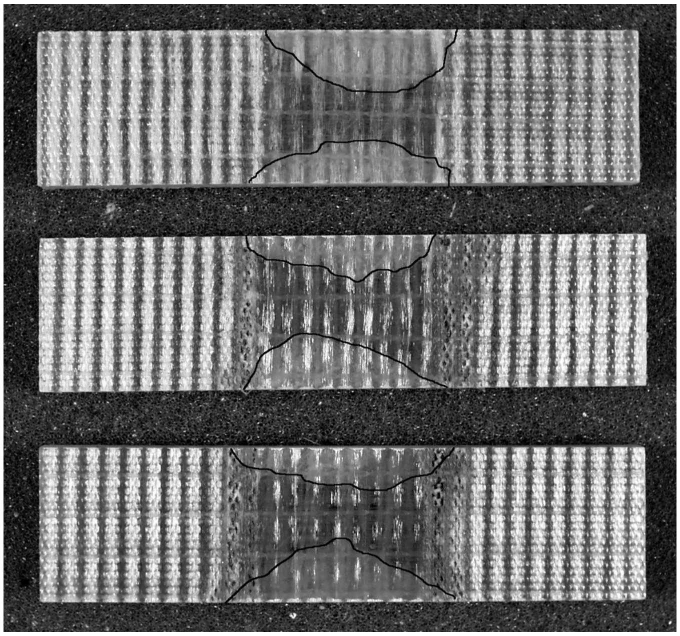


Figure 22. Compressive Coupons at Runout.

Reverse Loading Coupons

Specimens for reverse loading, R-value of -1, are subjected to both tensile and compressive loads and consequently show diverse and complex failure modes. Static tensile and compressive ultimate strengths are considerably different due to the different failure modes and mechanisms. Also, for a given maximum stress level, the reversing load case may be more detrimental to a laminate than either the tensile-tensile or compressive-compressive cases [14]. As a result, both the tensile-tensile and compressive-compressive coupon designs were considered for the reversing coupon design. A slightly modified tensile-tensile specimen proved successful in use for reverse loading fatigue tests. The elongated tabs aided in buckling resistance while providing a 12.7 mm gage section. The compressive-compressive design could not withstand the tensile loading portion of the reversing cycle due to grip failures.

Failures of these specimens were similar to that observed for the tensile only case. Figure 23 is a representation of failures of coupons subjected to reversing load spectra. Coupon number 1041 in Figure 23 was subjected to a constant amplitude reversing spectrum with a maximum and minimum stresses of ±103 MPa. The remaining three examples were specimens subjected to two-level block loading reversing spectra; with the two maximum stress levels of 172 and 103 MPa for the two blocks. The top specimen could have possibly been a compressive failure, yet pulled apart by the testing machine before it completely stopped. The bottom three examples exhibit similar failure characteristics of the tensile examples of Figure 20. None of the reversing failures were similar in appearance to the compressive failures of Figure 21.

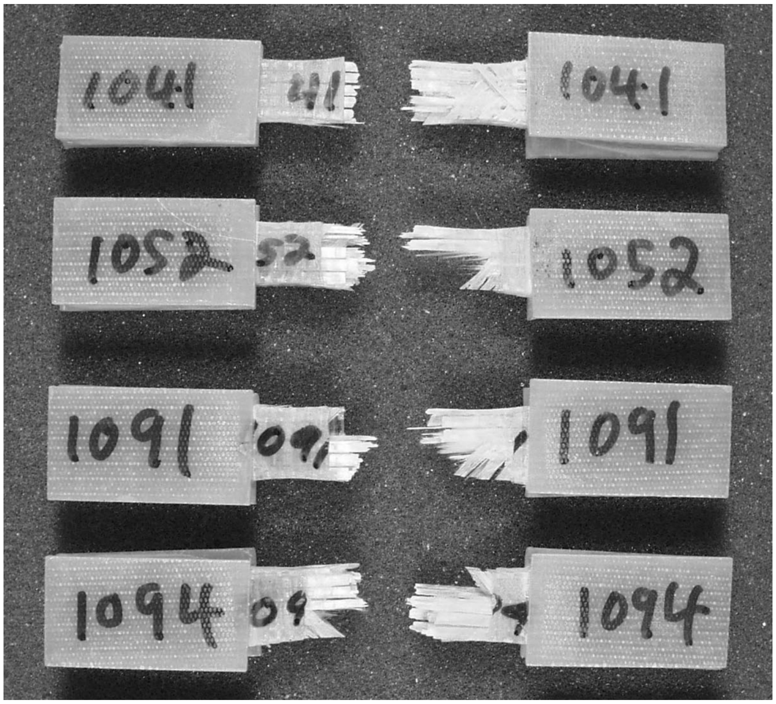


Figure 23. Reversing Coupon Failure Examples.

Testing Equipment

An Instron 8872 hydraulic testing machine with an Instron800 controller was used to subject the specimen to the spectrum loads. This testing machine, shown in Figure 24, was capable of producing ±20 kN of force over a displacement of ± 51 mm, with a 0.64 L/s servo-valve operating at 21 MPa. Specimens were affixed vertically between a stationary grip at the bottom and a moveable one at the top. These hydraulically actuated grips retain the specimen by wedging paired knurled grip faces towards each other, trapping the specimen. The upper set of grips could be moved vertically by means of varying hydraulic pressures within a cylinder. Pressure, in turn, was varied by regulating the flow of hydraulic fluid into and out of the cylinder by means of a servo valve. The servo valve received control signals from a microprocessor based controller of typical linear proportional, integral, and derivative design. Either position or load can be controlled. A variable differential transformer, LVDT, was used to measure position and a load cell to measure the force. Tuning or selection of the proportional, integral and derivative controller gains, was performed manually for different testing campaigns. A tuning method developed by Ziegler and Nichols [54] was used and resulted in the values shown in Table 3.

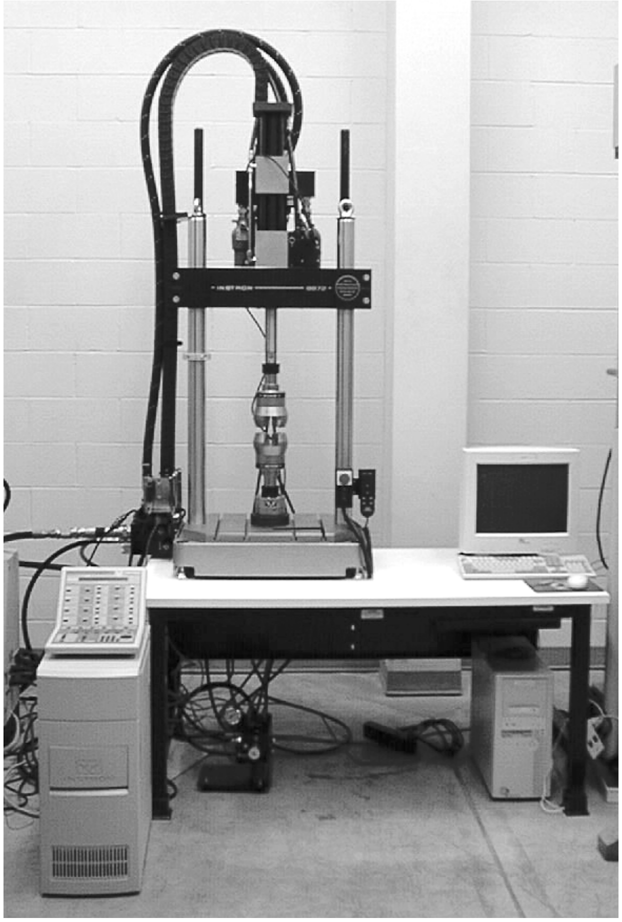


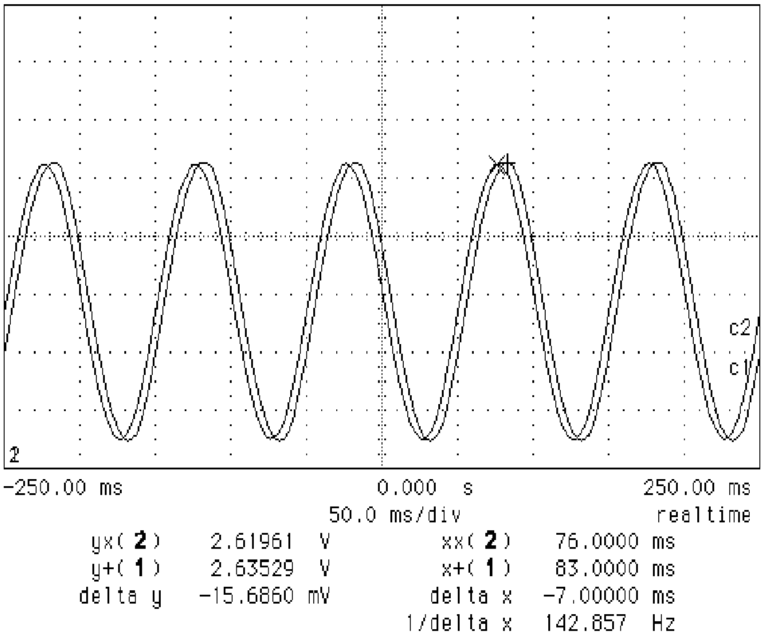
Figure 24. Instron 8872.

Table 3. Instron 8800 Controller Tuning Parameters

Testing Regime	Proportional Gain, dB	Integral Gain, s^{-1}	Derivative Gain, s	Lag, s
Tensile-tensile	-0.25	1.0	0.0	0.8
Compressive-compressive	+2.5	30.0	0.0	0.8
Reversing	+2.5	30.0	0.0	0.8
Amplitude control was not used.				

Performance of the hydraulic machine was dependent upon the frequency of cyclic motion or loading, as well as to the tuning of the controller, the material being tested, and the type of test. As with most systems, the greater the frequency of operation, the lower the amplitude capability.

Frequency response capability of the machine, along with concern for thermal degradation of the laminate under fatigue, led to performing tests at ten Hertz and less. Secondary measurement and recording of the actual loading waveforms, as shown in Figure 25, were favorably compared to that available from the Instron testing equipment.



```
yx( 2 )    2.61961  V        xx( 2 )    76.0000 ms
y+( 1 )    2.63529  V        x+( 1 )    83.0000 ms
delta y   -15.6860 mV        delta x   -7.00000 ms
                           1/delta x   142.857  Hz
```

Figure 25. Load Demand and Feedback Signals.

The maximum variation of the constant amplitude peak stress for R-values of 0.5, was within 1.5 percent of the mean, whereas the maximum variation of the constant amplitude valley stress was within 0.2 percent. Typical maximum stress and standard deviation for a 241 MPa constant amplitude fatigue test was 239.4 MPa and 0.338 MPa respectively. The maximum stress level generally decreased with time, due to the increased compliance of the specimen; consequently, greater motion was required to attain the loads.

The two-level block loading tests performed with the block loading software exhibited a low error in the maximum stress upon a change from a low amplitude cycle to a high amplitude cycle. Upon a change from a low stress level block to a high stress level block, the typical maximum variation of the peak value of stress was 0.2 percent. This relatively low error was probably achieved by the fact a ramp from one cycle mean to the next cycle mean was used to progress from one block to the next. Two-level block loading testing performed with the random loading software exhibited a higher error upon a change from a low amplitude stress cycle to a high amplitude stress level. The maximum error was 4 percent and occurred at the initiation of the test with the first cycle. Following errors were typically on the order of 2 percent.

Analysis of random spectrum loading revealed the greatest error (difference between demand and feedback) was upon start-up of the test; well removed from the maximum applied stress. The maximum error was less than 4 percent. The difference between the demand and feedback at the maximum stress cycle was less than 2 percent. Based upon the machine performance analysis, the Instron hydraulic testing apparatus was deemed acceptable for spectrum fatigue testing.

Control Software

Instron WaveEditor© (Version 6.2.00) and WaveRunner© (Version 6.4.0) software packages were primarily developed for block loading type of fatigue testing. The WaveEditor program was used to create the loading files that were subsequently used by the WaveRunner program for control of the hydraulic test machine.

Blocks of loading profiles could be defined as either ramps or sinusoids via WaveEditor. A ramp block was one in which a change in load from one level to another was specified to occur in a user entered amount of time. A sinusoidal block was one that was sinusoidal in shape, where the frequency, number of cycles, load mean and load amplitude were defined. Blocks could be specified to control either position or load. A constant amplitude test was prepared by the use of only one sinusoidal block, that was repeated until specimen failure. A spectrum of more than one sinusoidal loading block was prepared by a sequence of blocks, typically:

a) block one was a ramp from zero load to the mean of the first sinusoidal loading block; this was taken as a starter block
b) block two was a sinusoidal block
c) block three was a ramp from the mean load level of the block two to a mean load of the upcoming block four
d) block four was a second sinusoidal block
e) block five was a ramp from the mean of the fourth block to the mean of the second block.

Blocks two through five were then repeated until specimen failure. Additional blocks could be added when more than two load levels were desired. Once loading files were specified by the use of WaveEditor, actual control was accomplished by the use of WaveRunner.

The Instron software package, RANDOM©, was used to subject specimens to, as the name implies, random loading spectra. The function of the software was to sinusoidally load a specimen to a random spectrum when given a succession of peak and valley reversal points. A file containing the succession of peaks and valleys. Each line of the file contained a single reversal point. The contents of the file were scaled to a maximum (or minimum) value of one and signed for tension or compression. The entries format was “+#.####”, signed and four significant digits. Block loading could therefore easily be accomplished by the use of the RANDOM software package.

Early in fatigue testing, use of the WaveEditor and WaveRunner was discontinued since the RANDOM package would be required for the random spectrum fatigue testing and could also accomplish block fatigue testing. This was done to help preclude any anomalies that might be introduced by differences in software execution.

CONSTANT AMPLITUDE FATIGUE TESTING AND RESULTS

The fatigue testing in this research program, outlined previously, began with constant amplitude testing and progressed towards the implementation of more complex spectra. This first round of testing provided a set of baseline data that was compared to the results of other researchers and was used in the implementation of various life prediction models. Constant amplitude testing was performed at R-values of 0.1, 0.5, -1, 1, 2 and 10 to reasonably cover the significant regions of a Goodman diagram (Figure 7). The results of the constant amplitude fatigue tests were reduced to stress-cycle (S-N) diagrams. Regression analysis was performed for each data set assuming either an exponential (Equation 7) or power law (Equation 8) trend. The regression Equations are hereafter referred to as the fatigue models.

Constant Amplitude Test Results

The results of constant amplitude testing are recorded in raw and reduced form in Appendix B. Results at each R-value are summarized in a graphical form of stress-cycle (S-N) diagrams; Figures 26 through 30 are representations (on semi-log plots) of the constant amplitude fatigue of the laminate coupons for R-values of 0.1, 0.5, -1, 10 and 2.

Each S-N diagram was reduced to two fatigue models by performing both an exponential and power law regression of the respective data sets. The fatigue models were used in subsequent lifetime prediction rules or laws. These fatigue models take on the generic forms of Equations 7 and 8, which are repeated here for convenience, for the exponential and power law models, respectively

$$\frac{\sigma}{\sigma_0} = C_1 - b \log (N) \tag{7}$$

where σ = maximum applied stress, MPa

σ_0 = static strength, MPa

C_1 = regression parameter, frequently forced to unity to represent the static strength

N = number of cycles to failure

b = regression parameter related to the reduction in maximum applied stress for each decade increase in cycles

$$\frac{\sigma}{\sigma_0} = C_2 N^{-\frac{1}{m}} \tag{8}$$

Where C_2 = regression parameter
m = regression parameter, similar [30, 33] to the exponent in Equation 4

Table 4 contains the exponential regression parameters for each R-value as well as a comparison to the work of Samborsky [36] with the same laminate construction, yet from a different batch and specimen geometry.

Table 4. Exponential Regression Analysis Parameters for Constant Amplitude Fatigue of Material DD16 in DOE/MSU Fatigue Database, $[90/0/\pm45/0]_S$, (Table 2).

MPa	Range of Applicability	Regression Coefficients	R-Value, Equation 1				
			0.1	0.5	-1	10	2
Present Work UTS=632 UCS=400	1 to 10^7 Cycles	C_1	0.955	0.990	0.994	0.994	1.000
		b	0.120	0.107	0.125	0.081	0.062
		Correlation	0.938	0.942	0.975	0.955	0.927
	10 to 10^7 Cycles	C_1	0.849	0.920	0.722	0.963	1.006
		b	0.096	0.092	0.072	0.074	0.063
		Correlation	0.921	0.860	0.959	0.889	0.624
Reference [35] UTS=672 UCS=418	1 to 10^6 Cycles	C_1	1	-	-	-	-
		b	0.12	-	-	-	-

Comparison of the work reported in Reference [36] and this present work revealed no significant difference for the fatigue trend, b, for tests at R-values of 0.1. The ultimate tensile strengths were within 5.5 percent and the ultimate compressive strengths were within 4 percent.

The DD16 laminate used in this research may be considered to have an average fatigue sensitivity when compared to a family of similar laminates [14] comprised of E-glass and a polyester matrix and with a lay-up of zero and off-axis plies, reference Table 1, Chapter 2. The fatigue sensitivity (regression parameter b of Equation 9) in tension was reported in Chapter 2, to range from 0.1 to 0.14. The tension fatigue sensitivity of the DD16 material was 0.12 as shown in Table 4. The compression fatigue sensitivity of 0.08 falls in the range of 0.07 to 0.11 for the family of similar laminates. The DD16 reversing load fatigue sensitivity of 0.125 again falls in the range of 0.12 to 0.18 for similar cross-ply laminates.

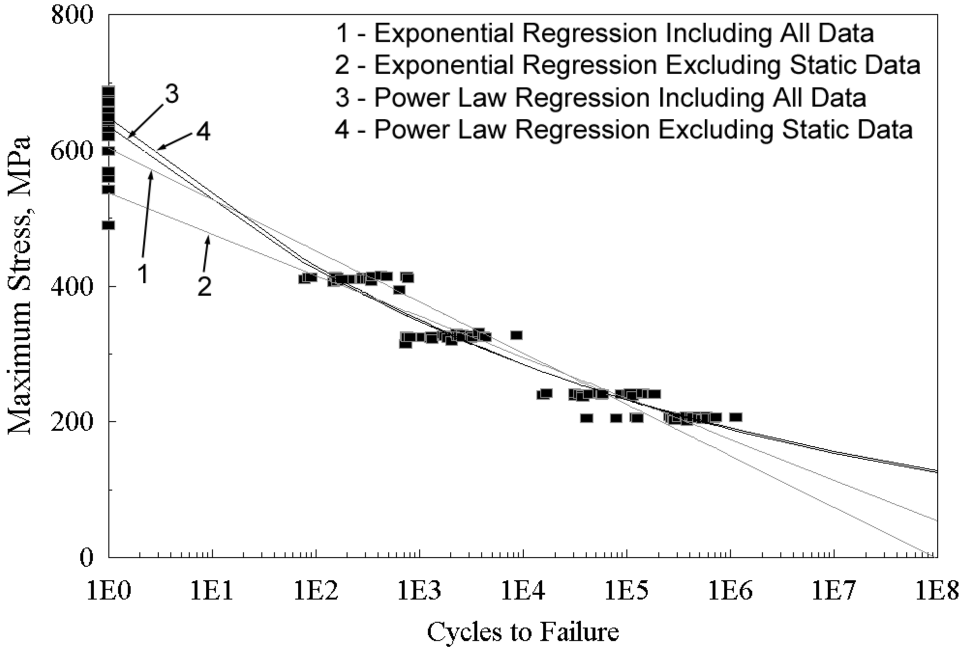


Figure 26. Constant Amplitude Fatigue for R = 0.1.

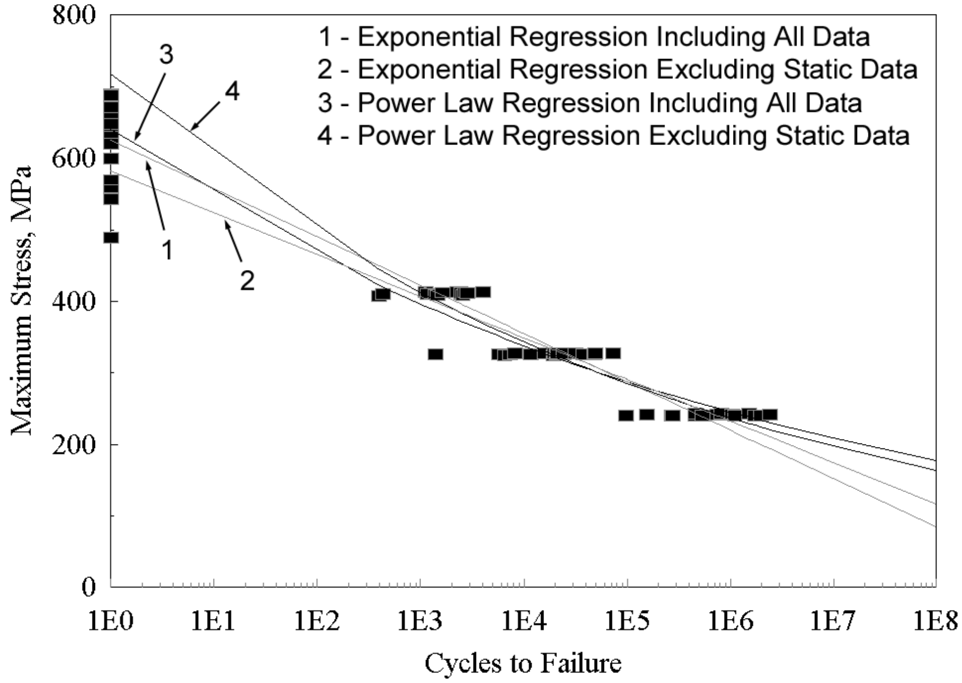


Figure 27. Constant Amplitude Fatigue for R = 0.5.

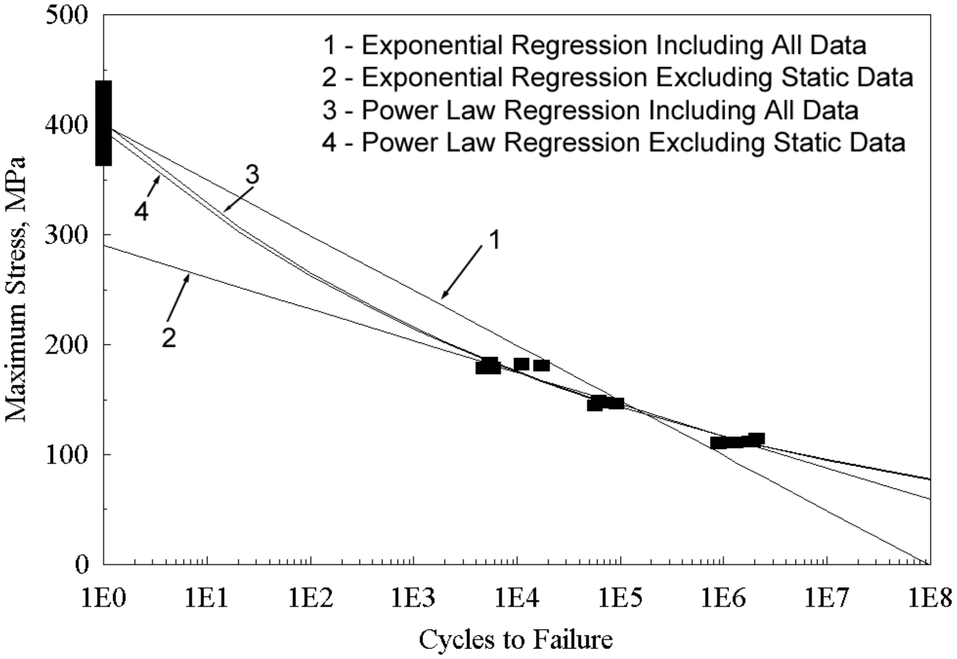


Figure 28. Constant Amplitude Fatigue for R = -1.

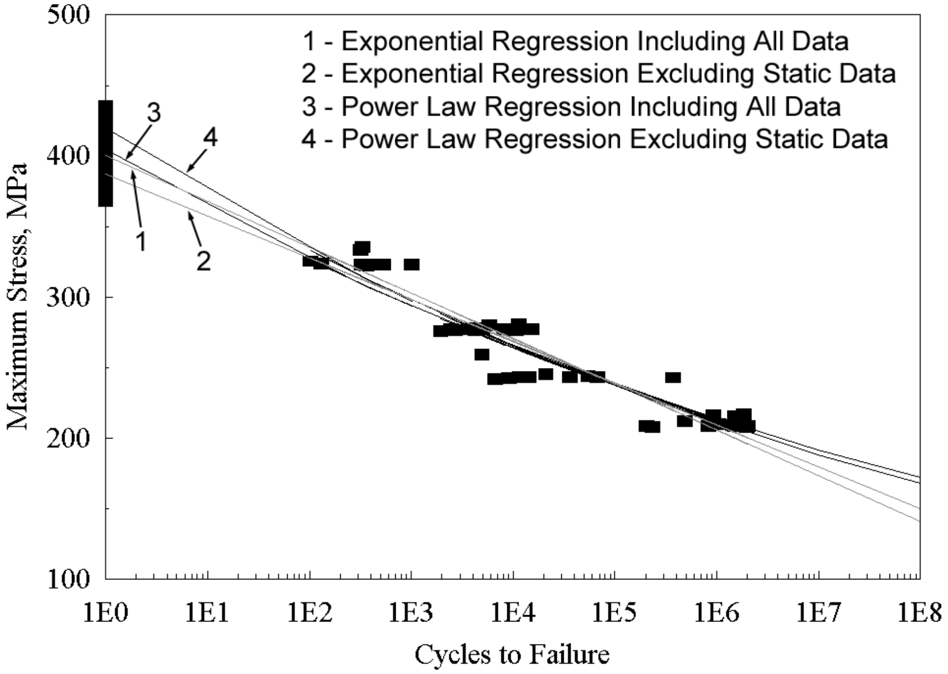


Figure 29. Constant Amplitude Fatigue for R = 10.

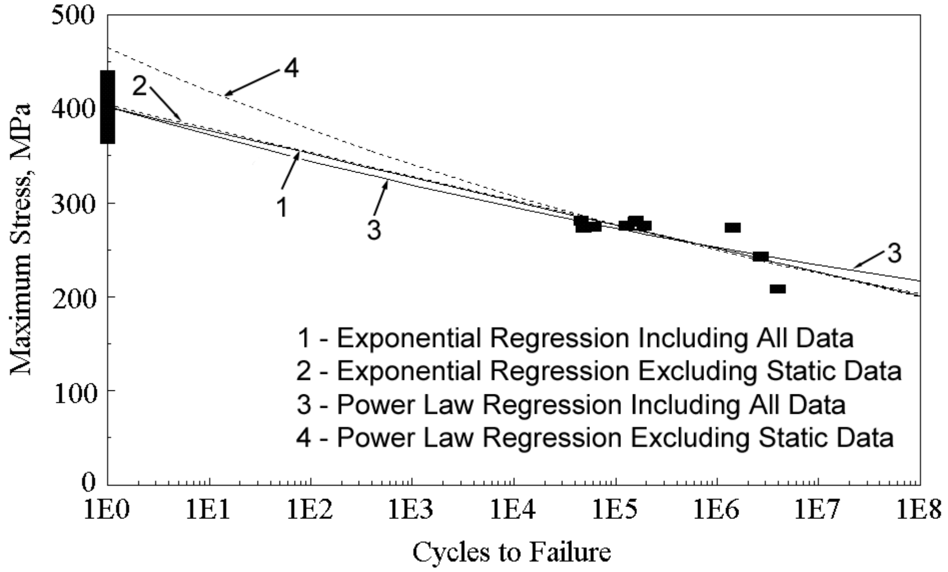


Figure 30. Constant Amplitude Fatigue for R = 2.

The fiber volume fraction of the DD16 laminate was 36 percent, placing this laminate in the class of better laminates' fatigue performance for this fiber volume fraction. The surface 90° plies of the DD16 laminate offered little in the material properties; their main purpose was aiding in mitigating grip effects. Discounting these surface plies places this laminate in the region of high 0° ply content (69 - 85 percent) where the fatigue trends of this laminate are in good agreement with that of similar laminates summarized in Table 1.

Table 5 contains the results of power law regressions at each R-value and comparisons to results of tests of uniaxial fiber lay-up material as reported by Sutherland [29]. Due to the difference in material, direct comparisons are not possible, yet trends can be compared and are similar.

The data of Tables 4 and 5 were also reduced to the graphical form of Goodman diagrams, Figures 31 through 34, and to the graphical form of regression lines, Figures 35 through 42. Note, in Figure 35, the relative order of the R-values, with the reversing condition being the more damaging (more rapid loss of life), followed by the tensile and lastly by the compressive load cases. This is consistent with the information displayed in the Goodman diagrams; note the closer spacing of the constant cycle lines for the compressive case, with the spacing increasing first for the tensile and lastly for the reversing.

Table 5. Power Law Regression Analysis Parameters for Constant Amplitude Fatigue

MPa	Range of Applicability	Regression Coefficients	R-Value, Equation 1				
			0.1	0.5	-1	10	2
Present Work UTS=632 UCS=400	1 to 10^7 Cycles	C_2	1.005	1.013	0.998	1.005	1.000
		m	11.478	14.400	11.158	21.550	29.820
		Correlation	0.966	0.946	0.993	0.961	0.933
	10 to 10^7 Cycles	C_2	1.026	1.135	0.981	1.043	1.155
		m	11.214	12.490	11.343	20.089	22.249
		Correlation	0.936	0.872	0.964	0.906	0.61
Reference [28] UTS=1422 UCS=720	1 to 10^8 Cycles	C_2	1	1	1	1	1
		m	11.3	15.4	14.9	18.0	31.2
	10^3 to 10^8 Cycles	C_2	0.969	0.977	1.124	0.862	0.859
		m	11.6	16.0	13.2	22.5	47.8
	10^5 to 10^8 Cycles	C_2	0.740	0.977	1.124	0.802	0.802
		m	14.3	16.0	13.2	24.9	61.7
Reference [54] UTS=392 UCS=298	10^3 to 10^8 Cycles	C_2	1.30	-	1.64	-	1.26
		m	10.5	-	9.34	-	21.7
	-	-	-	-	-	-	-
	-	-	-	-	-	-	-

Important information can be gleaned from a regression of the fatigue models, but not in a normalized format. Notice in Figures 39 through 42, that for moderate stress levels, there is a crossing of the curves for the tensile and compressive cases. At a given high absolute stress, compression is more damaging, while at low stresses, tension is more damaging.

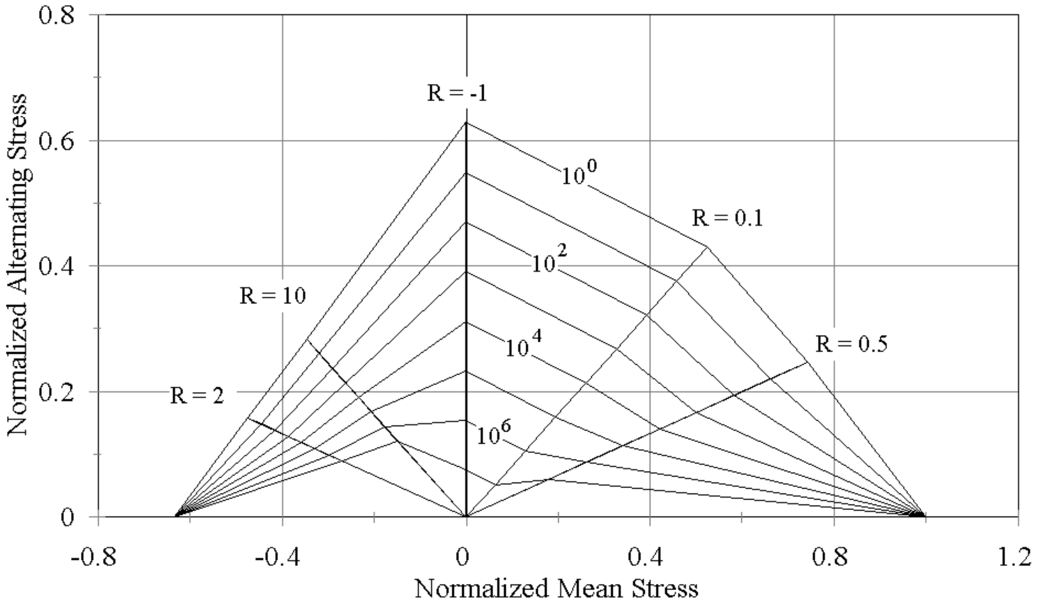


Figure 31. Goodman Diagram Based Upon Exponential Regression Analysis, Including All Data.

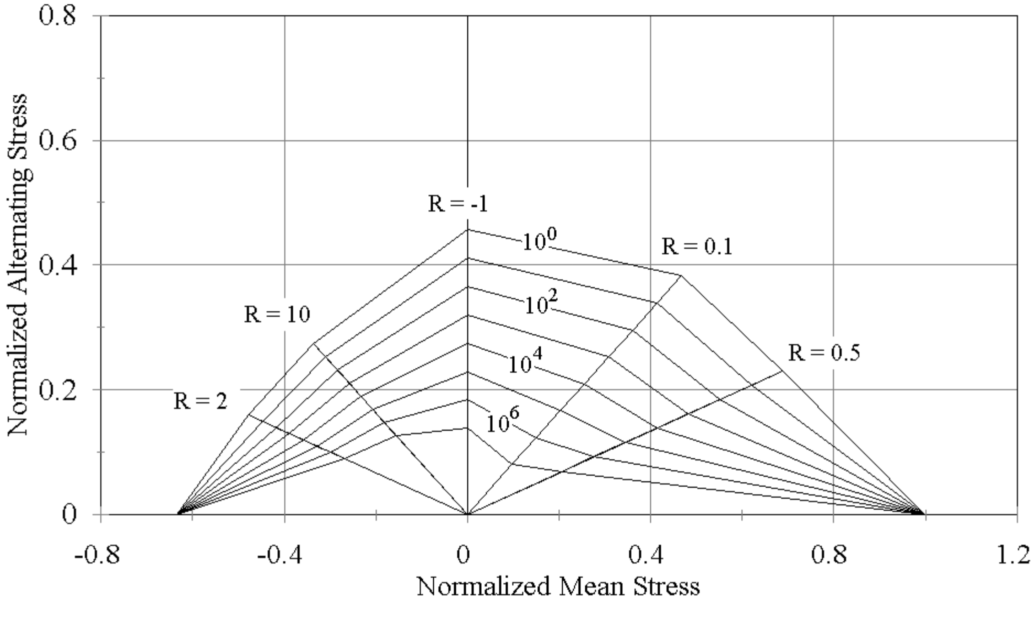


Figure 32. Goodman Diagram Based Upon Exponential Regression Analysis, Excluding Static Data.

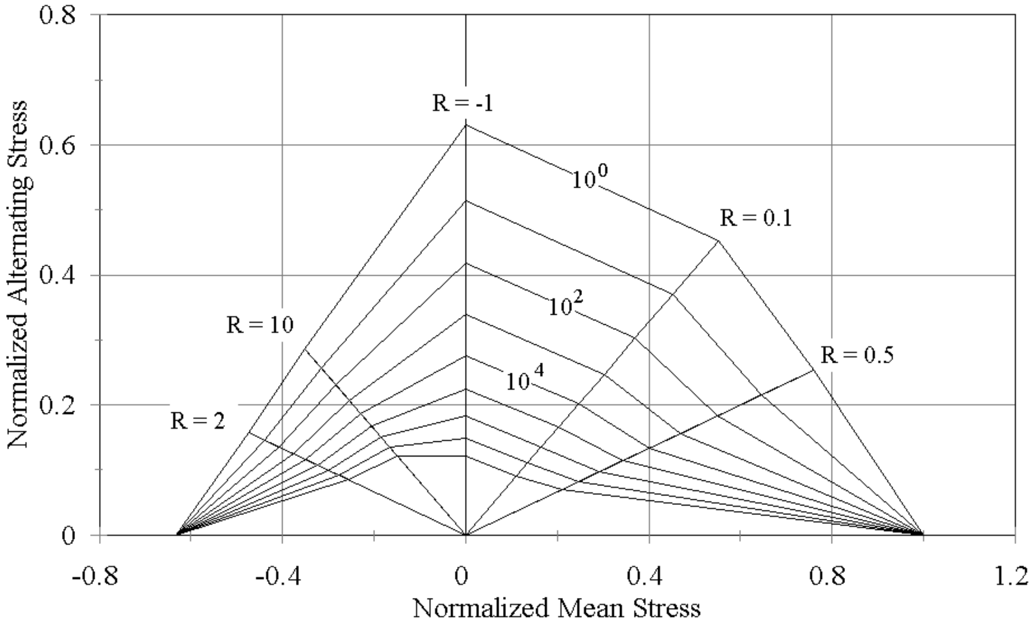


Figure 33. Goodman Diagram Based Upon Power Law Regression Analysis, Including All Data.

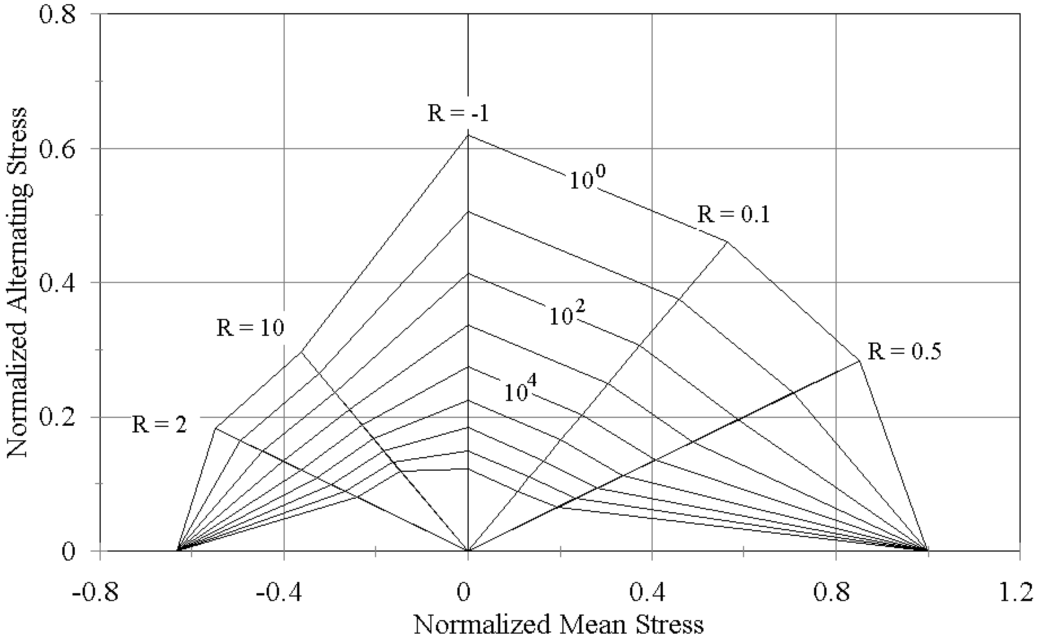


Figure 34. Goodman Diagram Based Upon Power Law Regression Analysis, Excluding Static Data.

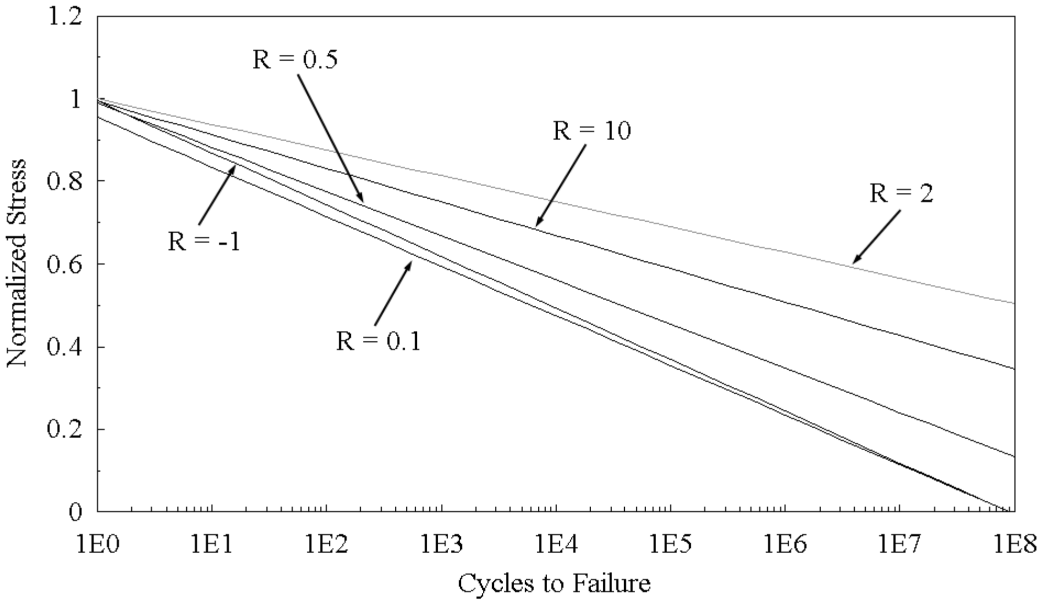


Figure 35. Normalized Fatigue Models, Exponential Regression Including All Data.

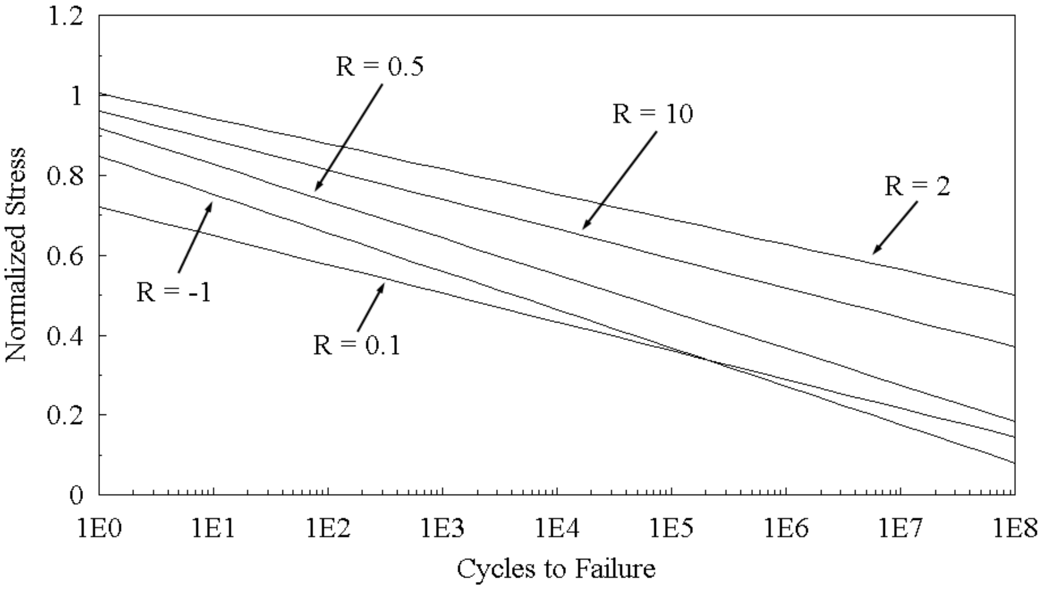


Figure 36. Normalized Fatigue Models, Exponential Regression Excluding Static Data.

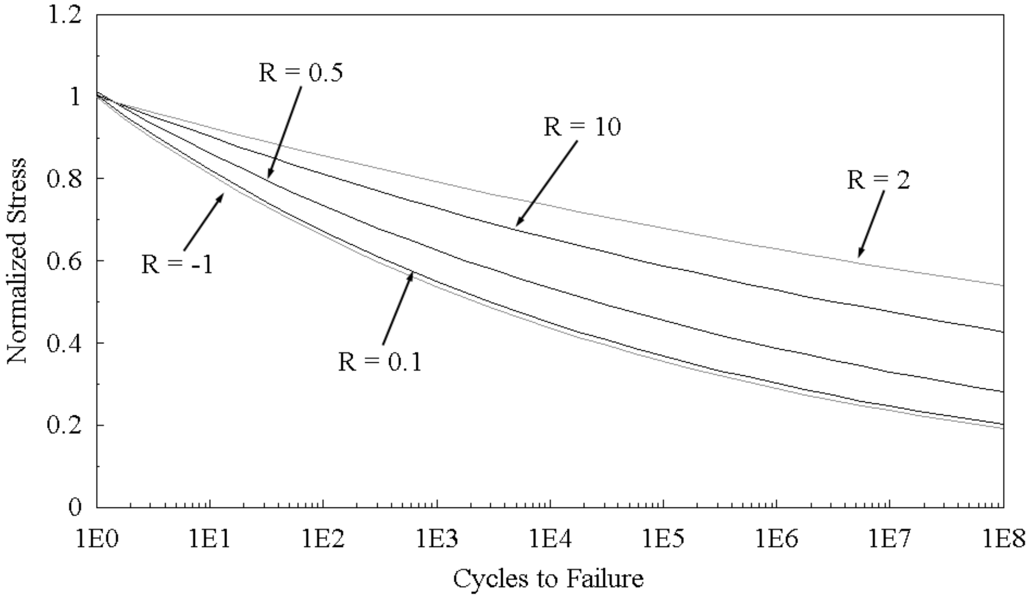


Figure 37. Normalized Fatigue Models, Power Law Regression Including All Data.

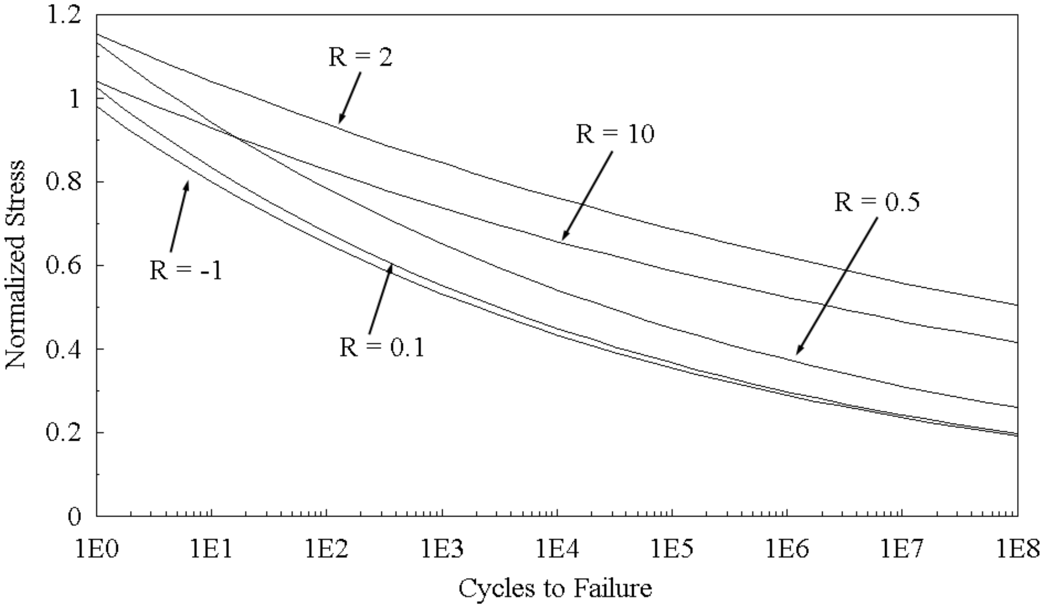


Figure 38. Normalized Fatigue Models, Power Law Regression Excluding Static Data.

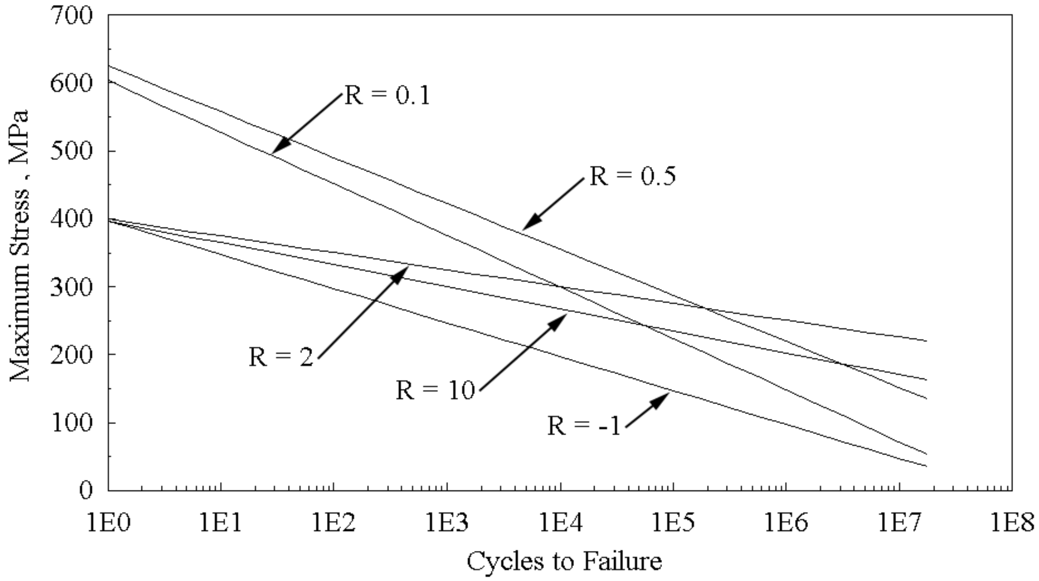


Figure 39. Exponential Fatigue Regression Models For All R-Values Including All Data.

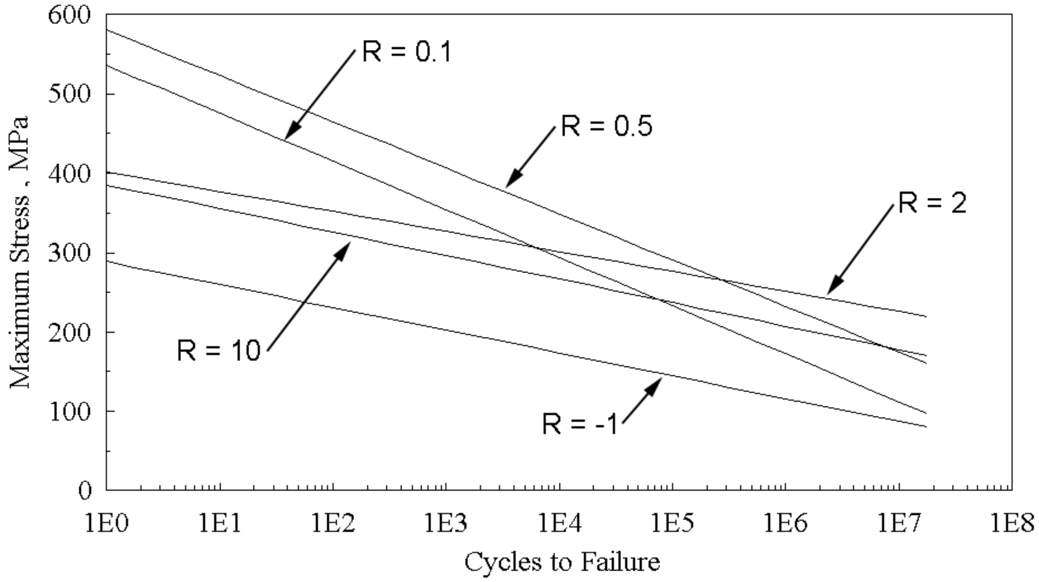


Figure 40. Exponential Fatigue Regression Models For All R-Values Excluding Static Data.

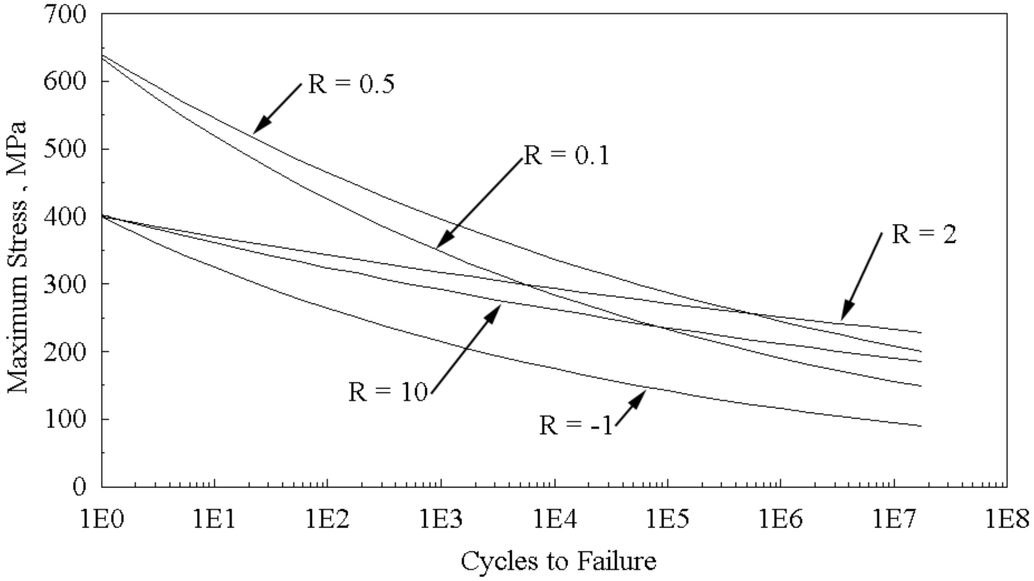


Figure 41. Power Law Fatigue Regression Models For All R-Values Including All Data.

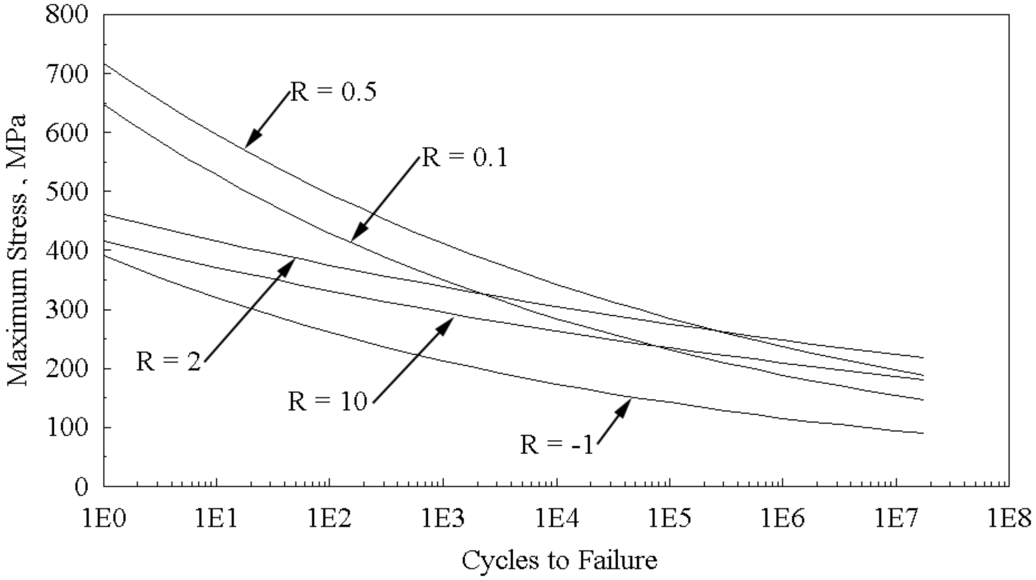


Figure 42. Power Law Fatigue Regression Models For All R-Values Excluding Static Data.

Residual Strength of Laminate Under Fatigue

The general trend of the residual strength of a laminate over its life was previously discussed. Recall that the shape of the strength curve, as related to the number of cycles experienced, can drastically affect lifetime predictions. Attempts were made to perform partial fatigue tests in order to ascertain the residual strength parameter, ν. Specimens were subjected to selected constant amplitude stress levels for a fixed number of cycles. The ultimate strengths of the cycled specimens were measured and compared with the ultimate strength of virgin, un-fatigued, specimens. Residual strength tests have been run for specimens subjected to fatigue at R-values of 0.1 and 0.5.

Figure 43 presents the residual strength results for the laminate subjected to 241 MPa with an R-value of 0.1. Tabulated data were taken from Reference [36] and placed into the graphical form of Figure 43. Specimens were fatigued to cycle accumulations at three different levels, 50,000, 100,000, and 200,000 cycles. Some specimens failed prior to achieving the desired cycle level and are so noted. Also shown and labeled as S-N fatigue, are the results of specimens cycled until failure as well as the virgin material ultimate tensile strength test results. It is evident from the residual strength data collected, that the residual strength parameter, ν, is not greater than unity. The premature failure of specimens before reaching the desired number of cycles complicates the analysis of a reasonable value for ν. Regardless, upon investigating the residual strength results for both R-values of 0.1 and of 0.5, a factor of less than one was considered appropriate. The residual strength tests, summarized in Figure 44, were performed at a maximum stress level of 325 MPa and at an R-value of 0.5.

The general shape of the residual strength lifetime curves (Equations 13 and 14) is uncertain. An error analysis of the residual strength data shown in Figure 43 indicates the nonlinear strength degradation curve yields a mean absolute minimum error of 23 percent with a degradation parameter, ν, of 0.265. The linear residual strength curve analysis indicated a mean absolute error of 37 percent. The results of this work and that of Reference [36] indicate that the nonlinear parameter, ν, is not greater than one. Broutman and Sahu [43] data seems to indicate that a linear residual strength degradation is valid; while Yang and Jones [37] indicate (without data) that a nonlinear strength degradation parameter greater than one is reasonable. This parameter may be a function of the laminate as well as the stage of life of the material.

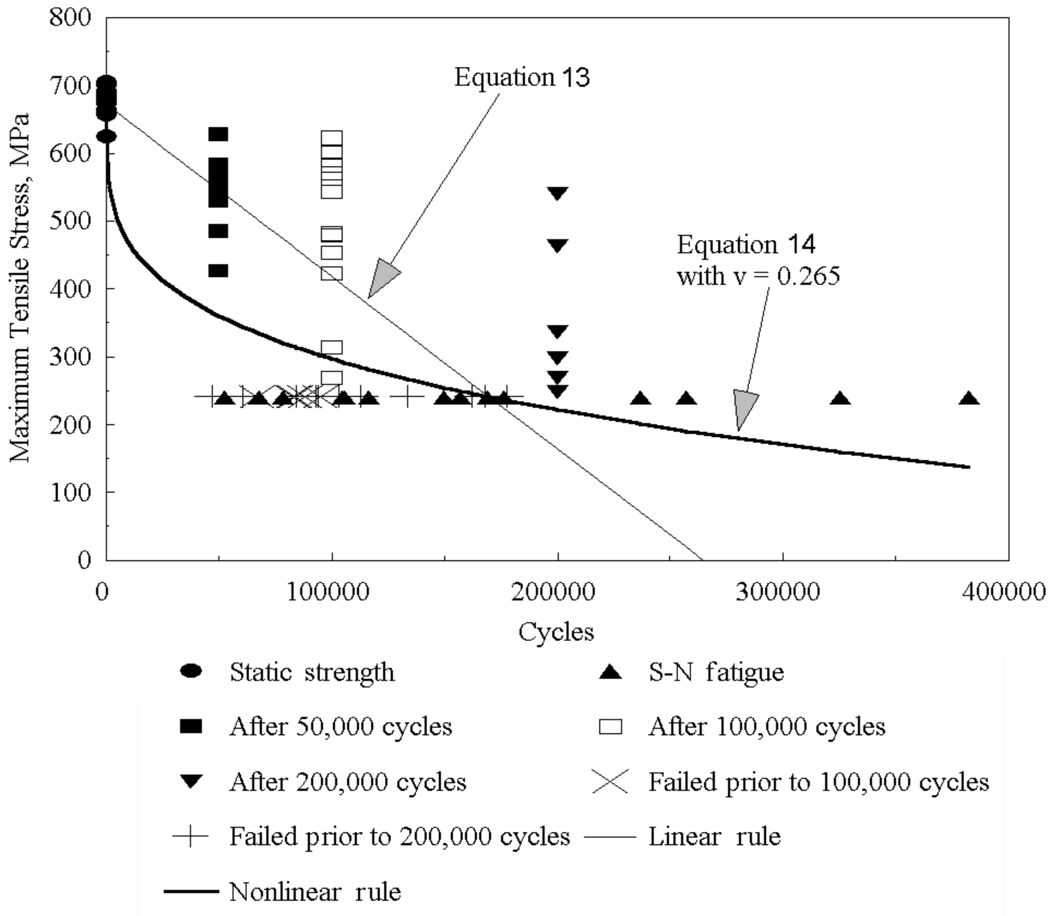


Figure 43. Residual Strength Data For R = 0.1 [36].

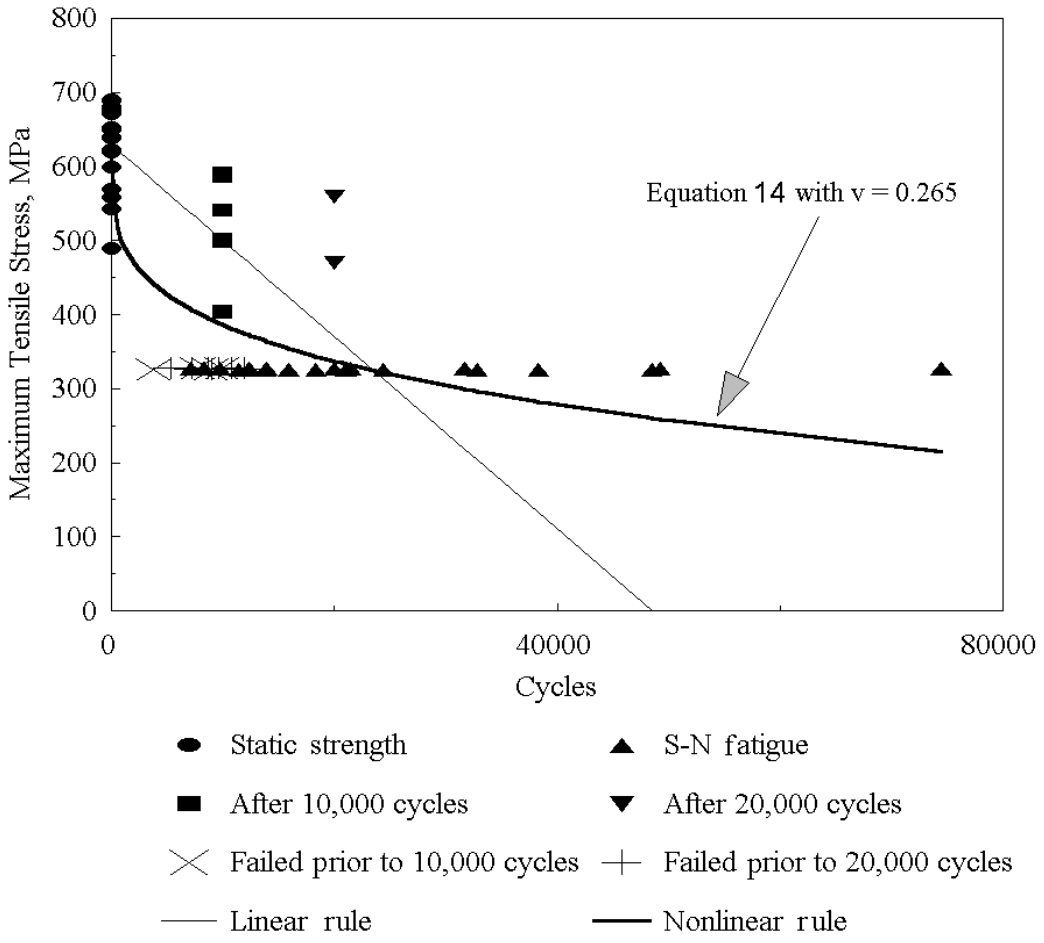


Figure 44. Residual Strength Data For R = 0.5.

An investigation into variable amplitude fatigue testing logically begins with two amplitudes or stress levels before considering more complex spectra. Other researchers have also taken this approach, implementing a spectrum of one block of constant amplitude cycles followed by a second block of different constant amplitude cycles. The second block was run until specimen failure in tests by Yang, et. al. [11].

Testing in this format is not considered representative of a realistic spectrum; consequently, an alternate application of two-level block loading testing was considered for this research. Upon considering a standard European spectrum for wind turbine blades, it is evident that a repetition of blocks would be more appropriate. Note the obvious repetitions in the time-compressed European spectrum WISPER [16, 17] shown in Figure 45.

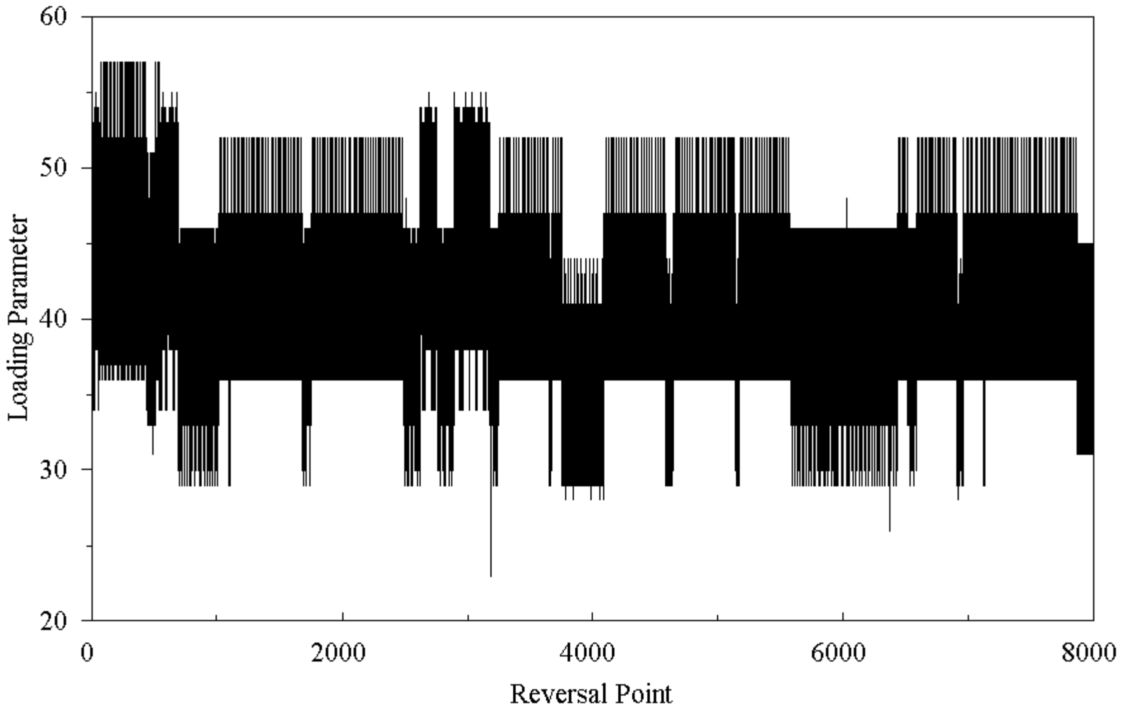


Figure 45. Excerpt of WISPER Spectrum.

Sequence Effects

When entering into studies of fatigue at two different load levels, thought must be given to possible effects of the sequencing of the cycles. This is prompted by the result of fatigue analysis in metals by linear elastic fracture mechanics [23]. In metals, a high load can create a compressed region at the crack tip, thereby retarding crack growth at lower loads, and consequently extending fatigue life.

Three separate spectra containing the same number of cycles at each stress level were developed for investigation of possible sequence effects in the fatigue of this laminate. The three spectra are shown in Figure 46. The first contains a block of one high amplitude cycle followed by 100 low amplitude cycles. These two blocks are shown repeated ten times to create a spectrum of 1010 cycles in length. The second spectrum was comprised of ten high amplitude cycles followed by 1000 low amplitude cycles. The third was constructed to contain ten high amplitude cycles randomly interspersed within 1000 low amplitude cycles. The same block of random sequences was repeated for each pass until coupon failure. The high amplitude cycle fraction is defined as the number of high amplitude cycles divided by the total number of cycles. Each of these spectra, then, had a high amplitude fraction of approximately 0.01.

High amplitude cycles were set at an R-value of 0.1 and had a maximum stress of 325 MPa. Low amplitude cycles were also set at an R-value of 0.1, but at a maximum stress of 207 MPa. Figure 47 details the results of 120 tests, 82 two-level block loading and 38 reference constant amplitude tests. The fraction of specimen failures is displayed against the total number of cycles experienced. All of the specimens are from the same batch of fabric reinforcement, and tests were randomly interspersed between the different sequences and the constant amplitude cases.

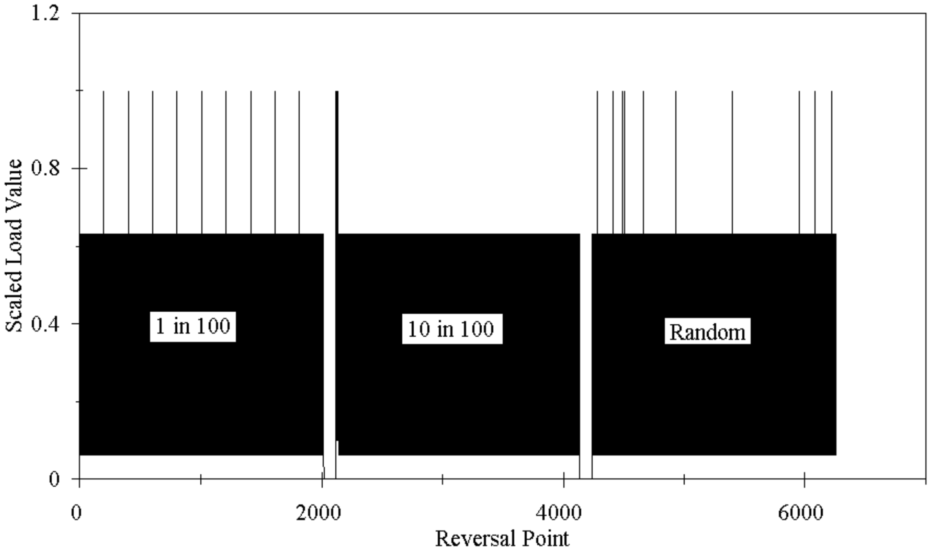


Figure 46. Two-level block loading Sequences (Blocks Repeated to Failure).

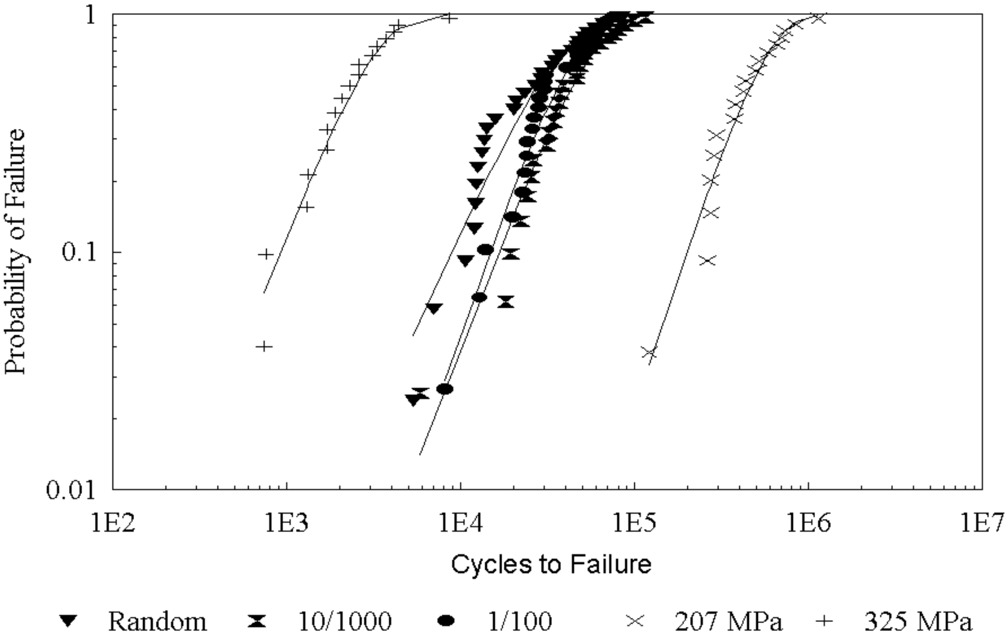


Figure 47. Two-Level Block Loading Sequence Test.

Within confidence limits of 0.95, there is no statistical difference among the three sequences. Consequently, sequencing was not considered important and was ignored for the remainder of the testing.

Only four of the 82 sequencing effect tests achieved Miner's sums greater than unity. In fact the average Miner's sum is slightly less than 0.3, as evident in Figure 48. Compare this against the average Miner's sum of 1.0 for the constant amplitude fatigue tests and it becomes evident that spectral loading does not produce failure at a Miner's sum averaging 1.0. This phenomenon will be investigated later on.

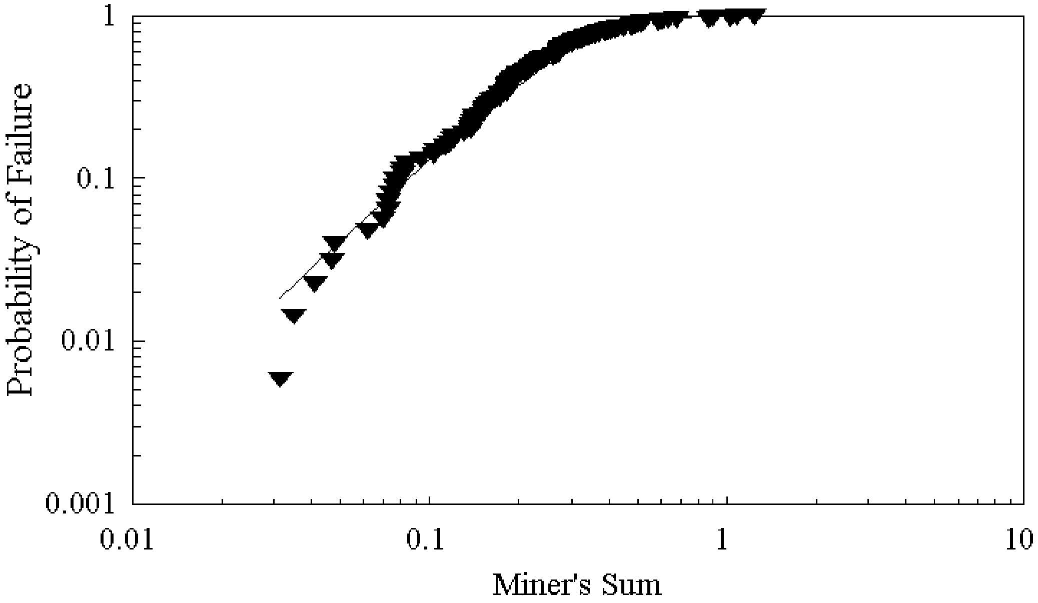


Figure 48. Overall Two-level block loading Miner's Sum, Stresses 325 and 207 MPa (Load Ratio = 1.57), High Amplitude Cycle Ratio of 0.01.

Two-level block loading Fatigue Testing

Two-level block loading testing was performed at several combinations of stress levels as well as for different R-values using the different sequences shown in Figure 46. Testing was performed for cases in which the two stress levels were relatively close as well as distant. Test campaigns are identified in Table 6. The cycles column gives the number of cycles per block; blocks are repeated until failure in all cases.

Table 6. Two-level block loading Testing Campaigns

High Stress Block			Low Stress Block			
σ_{max}, MPa	R-value	Cycles	σ_{max}, MPa	R-value	Cycles	Load Ratio
414	0.1	10	325	0.1	10, 90, 100, 990, 1K, 9K	1.27
414	0.1	10	235	0.1	10, 90, 100, 112, 1K, 10K	1.76
325	0.1	10	235	0.1	10, 100, 500, 1K, 3K, 5K	1.38
325	0.1	10	207	0.1	10, 50, 90, 100, 1K, 3K, 5K, 10K, 20K, 33K, 50K, 60K	1.57
235	0.1	10, 20	207	0.1	10, 90, 100, 990, 1K, 9K, 33K, 50K, 60K	1.13
414	0.5	10	325	0.5	10, 50, 100, 1K	1.27
414	0.5	10	235	0.5	10, 100, 1K, 10K	1.76
325	0.5	10	235	0.5	10, 90, 100, 1K, 10K	1.38
235	0.5	10	207	0.5	90	1.14
-276	10	10, 1K, 10K	-207	10	10, 100, 1K, 10K	1.33
-325	10	10	-207	10	10, 100, 1K, 10K	1.57
173	-1	10	104	-1	10, 100, 1K, 10K	1.66

One would expect that as the two stress levels approached each other in magnitude, any effects on fatigue would diminish, the limiting case being of constant amplitudes. Tests were arranged to allow investigation of this possibility.

Results of two-level block loading fatigue testing have been summarized into graphical form (Figures 49 - 70) relating the Miner's sum to the fraction of high amplitude cycles. A fraction of high amplitude cycles of zero would, in reality, be a constant amplitude test of the lower stress level. Conversely, a fraction of one would indicate a constant amplitude test at the higher stress level. In each of the following two-level block loading graphs, the abscissa has been broken into two parts, the extreme left is of a linear scale, allowing the zero fraction to be displayed; the remainder of the scale to the right is logarithmic. Included in each graph are lifetime predictions that will be discussed in a following section. Within the legend of each graph, NRSD and LRSD refer to a Nonlinear and Linear Residual Strength Damage models, respectively. The NRSD cases were all run with $\nu = 0.265$. The graphs are presented in pairs, on one page, with the upper displaying the lifetime predictions based upon an exponential fatigue model (Equation 7); the lower represents lifetime predictions based upon a power law fatigue model (Equation 8).

Note, in most of these figures that the trend of Miner's number varies from one at the left hand margin (low stress level constant amplitude fatigue test) to less than one and finally back towards an average of one at the right hand margin (high stress level constant amplitude fatigue test). There does not appear to be a retardation effect observable in the multi-block fatigue of the tested laminate.

The degrading effect of load interaction (Miner's sums below 1.0) was most prevalent in the tensile tests at R-values of 0.1 and 0.5, with the effect greater for the larger spread of the applied maximum stress levels. The effect was also observed in the reversing load cases, and R-value of -1; and to a much lesser extent in the compressive cases of the R-values of 2 and 10.

A tabulated form of the test results and calculations for all two-level block loading testing campaigns can be found in Appendix C.

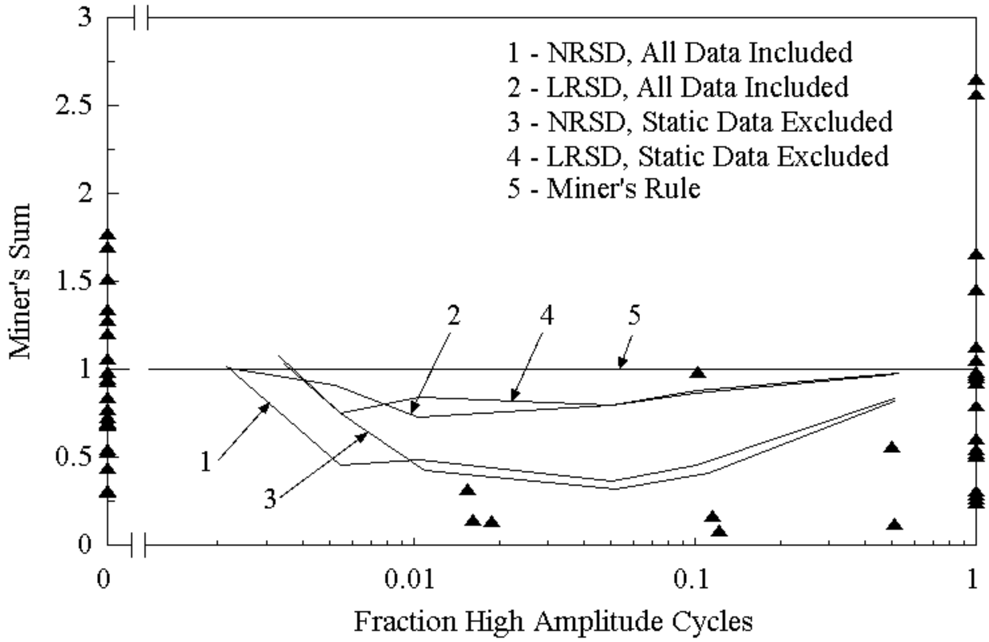


Figure 49. Two-level block loading Test Results for R = 0.1, 414 & 325 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

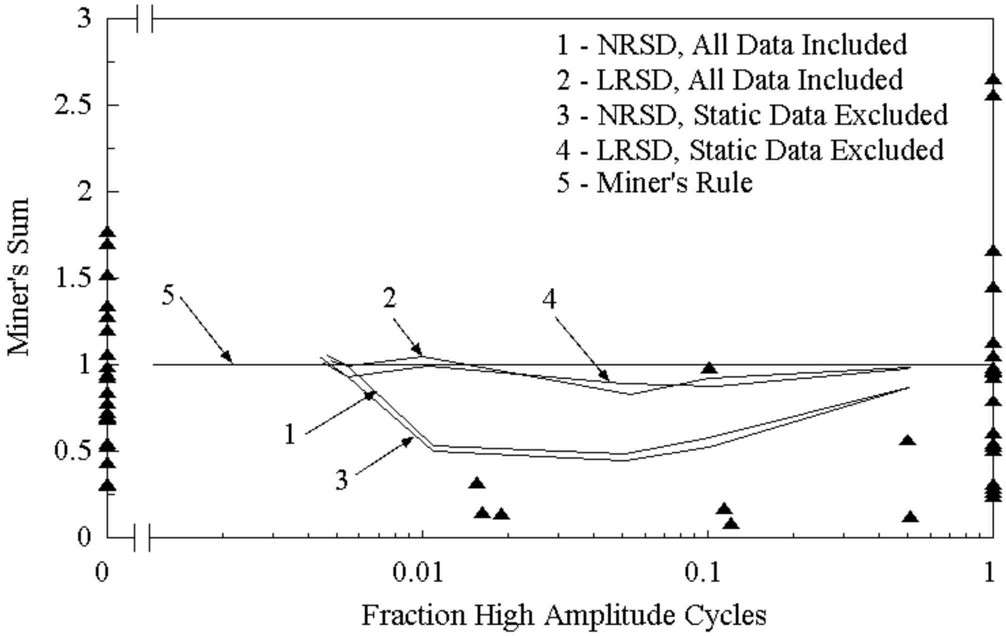


Figure 50. Two-level block loading Test Results for R = 0.1, 414 & 325 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

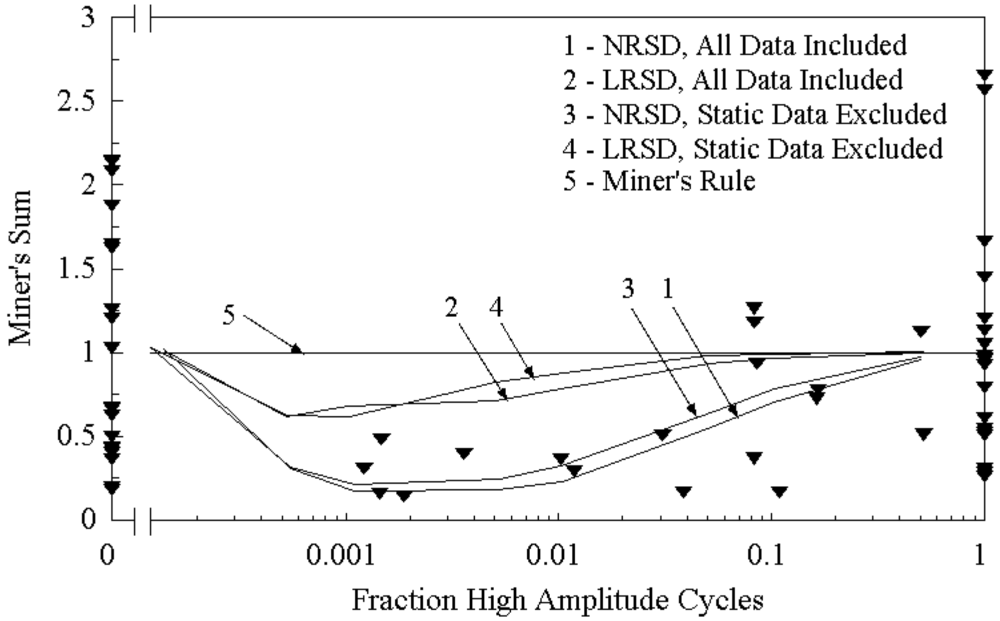


Figure 51. Two-level block loading Test Results for R = 0.1, 414 & 235 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

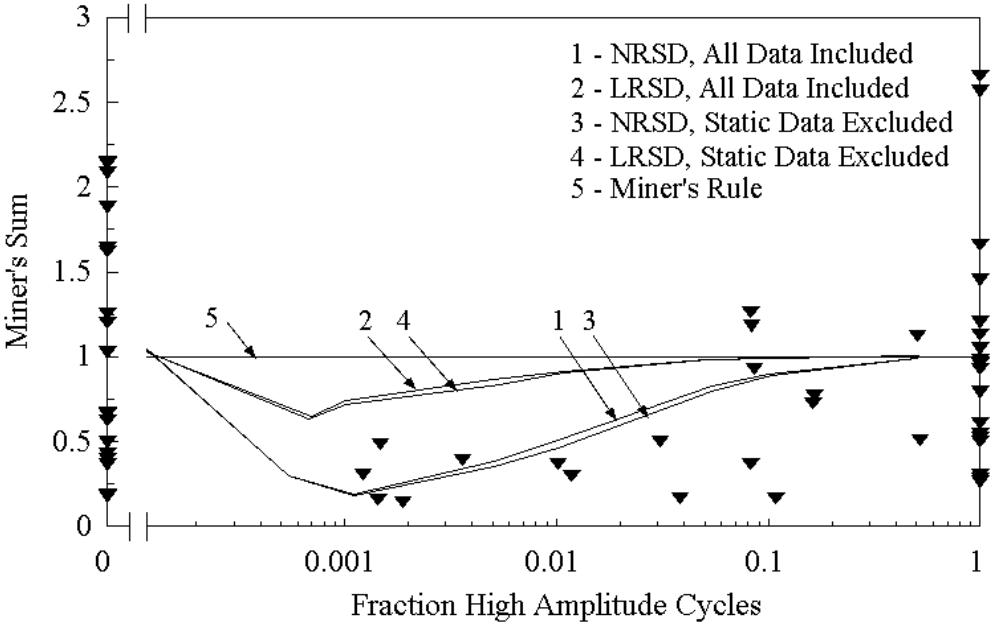


Figure 52. Two-level block loading Test Results for R = 0.1, 414 & 235 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

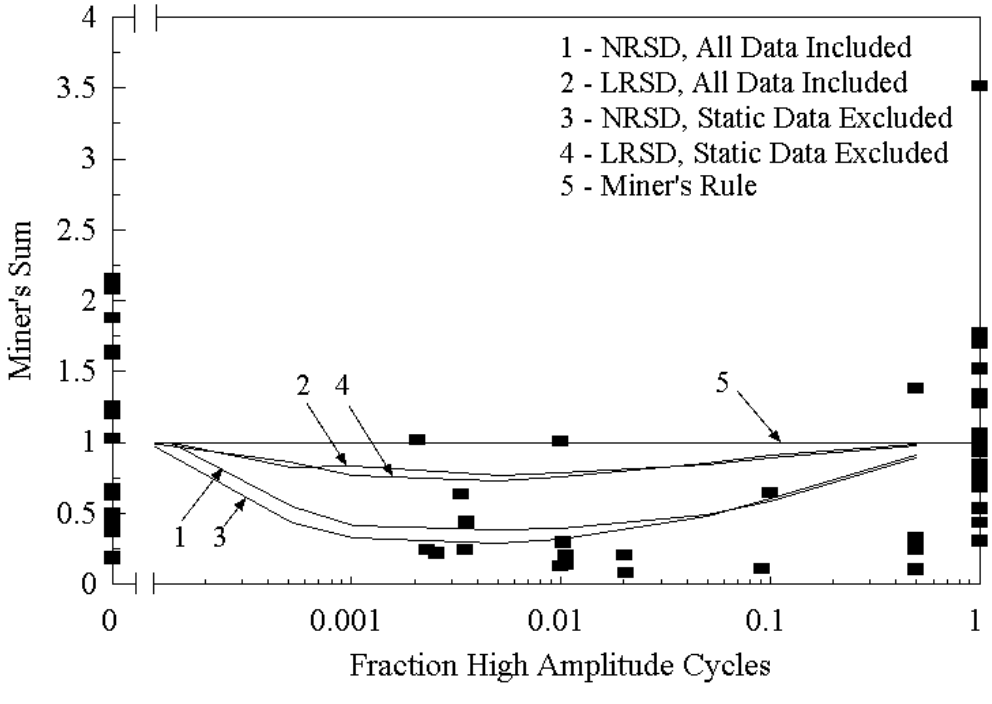


Figure 53. Two-level block loading Test Results for R = 0.1, 325 & 235 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

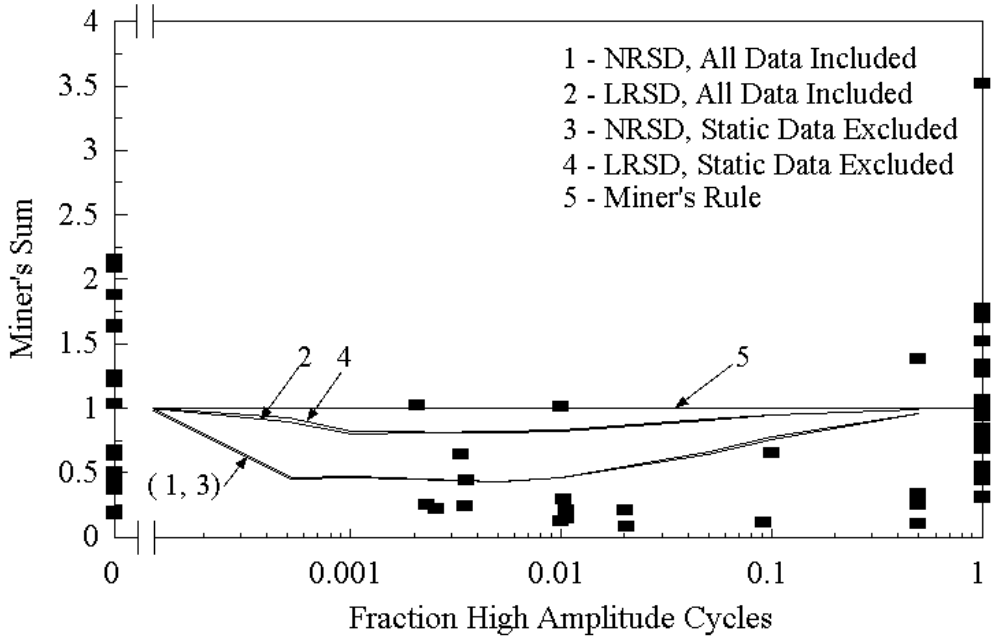


Figure 54. Two-level block loading Test Results for R = 0.1, 325 & 235 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

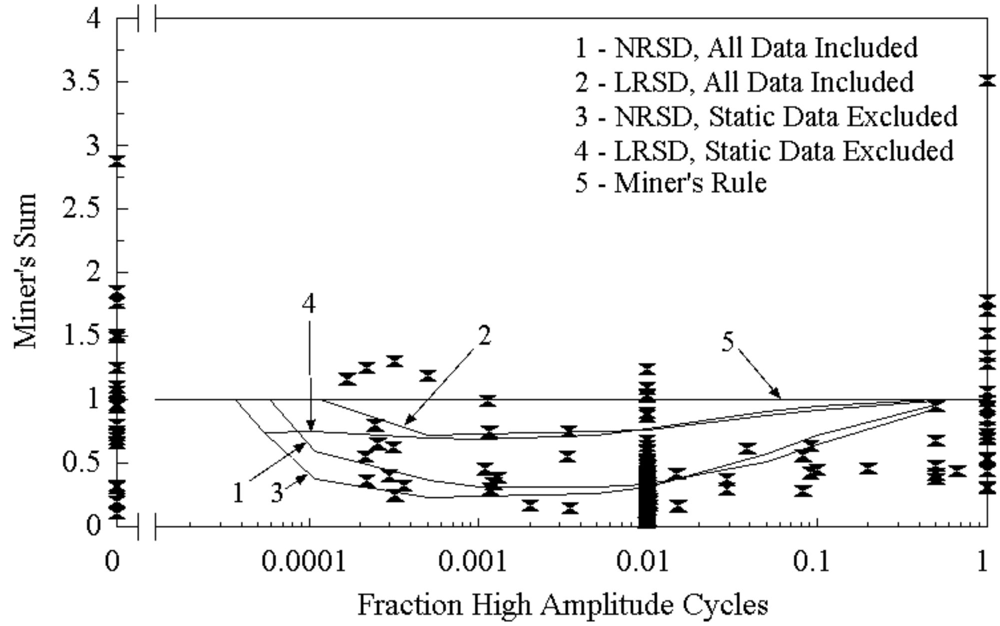


Figure 55. Two-level block loading Test Results for R = 0.1, 325 & 207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

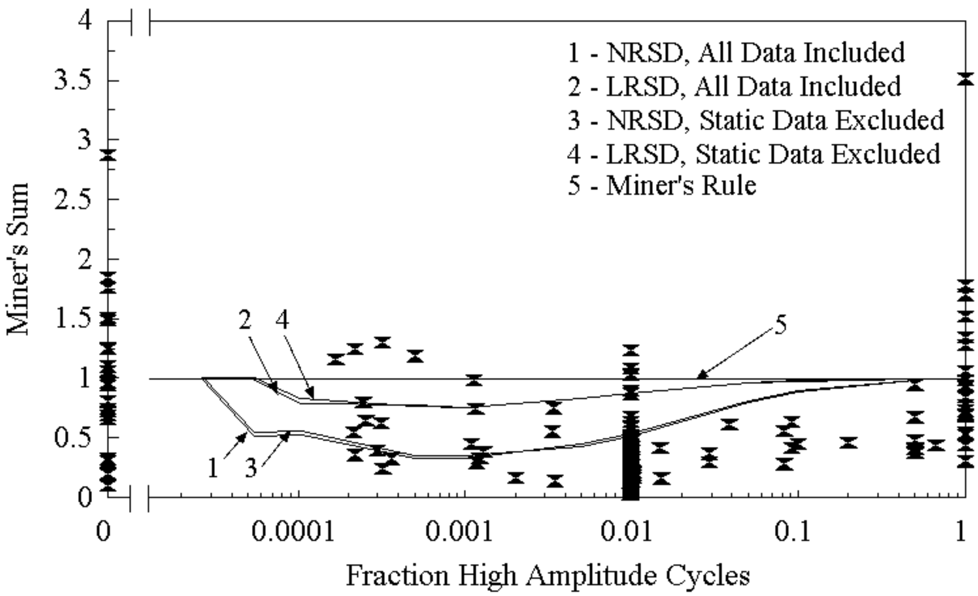


Figure 56. Two-level block loading Test Results for R = 0.1, 325 & 207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

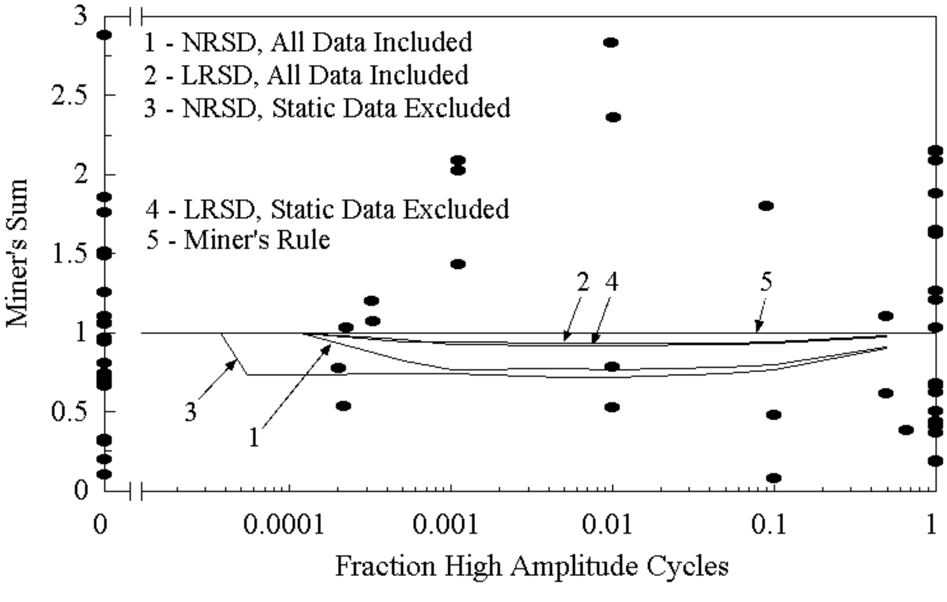


Figure 57. Two-level block loading Test Results for R = 0.1, 235 & 207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

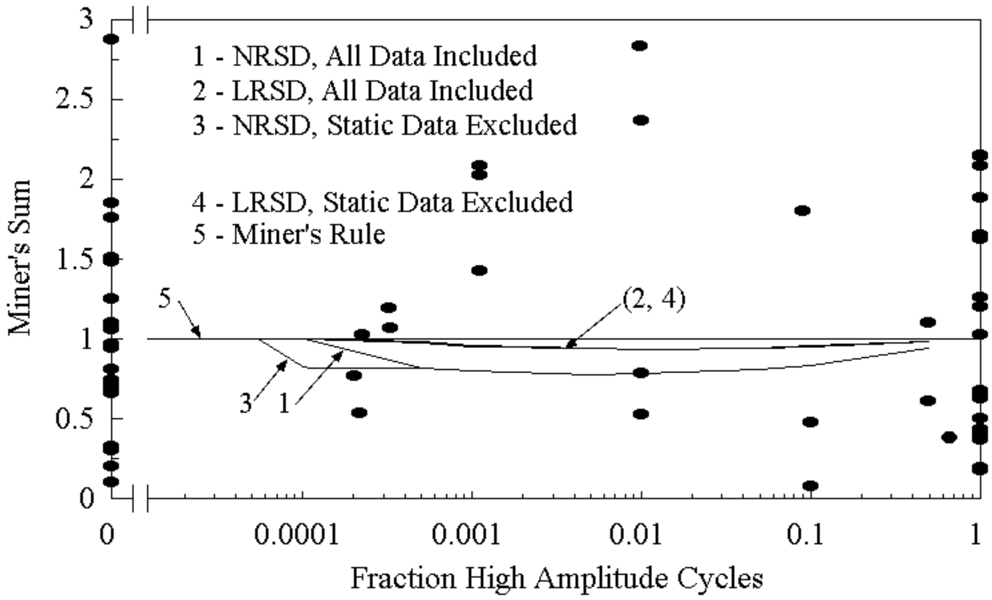


Figure 58. Two-level block loading Test Results for R = 0.1, 235 & 207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

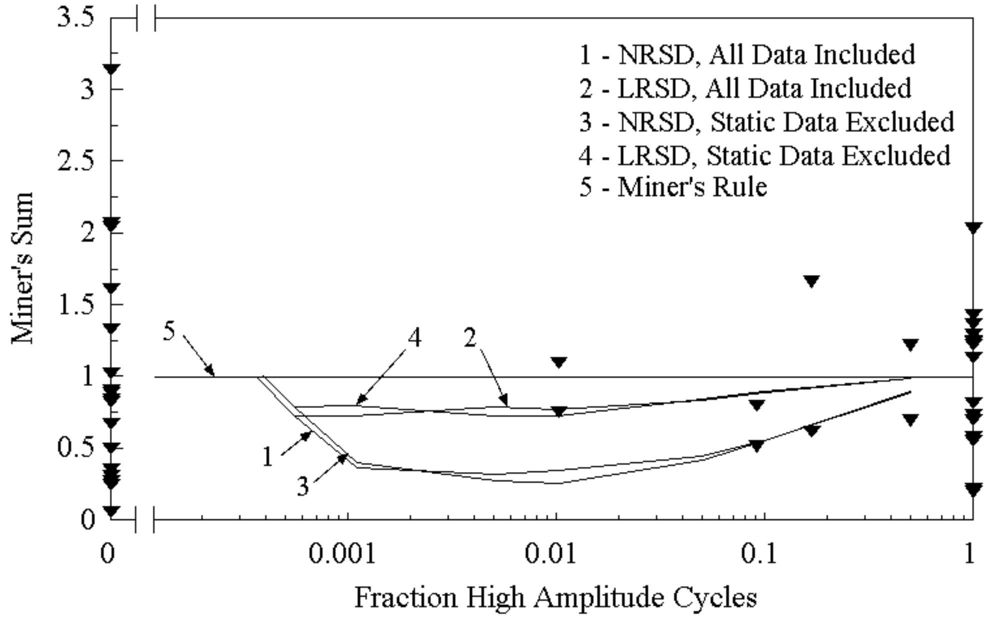


Figure 59. Two-level block loading Test Results for R = 0.5, 414 & 325 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

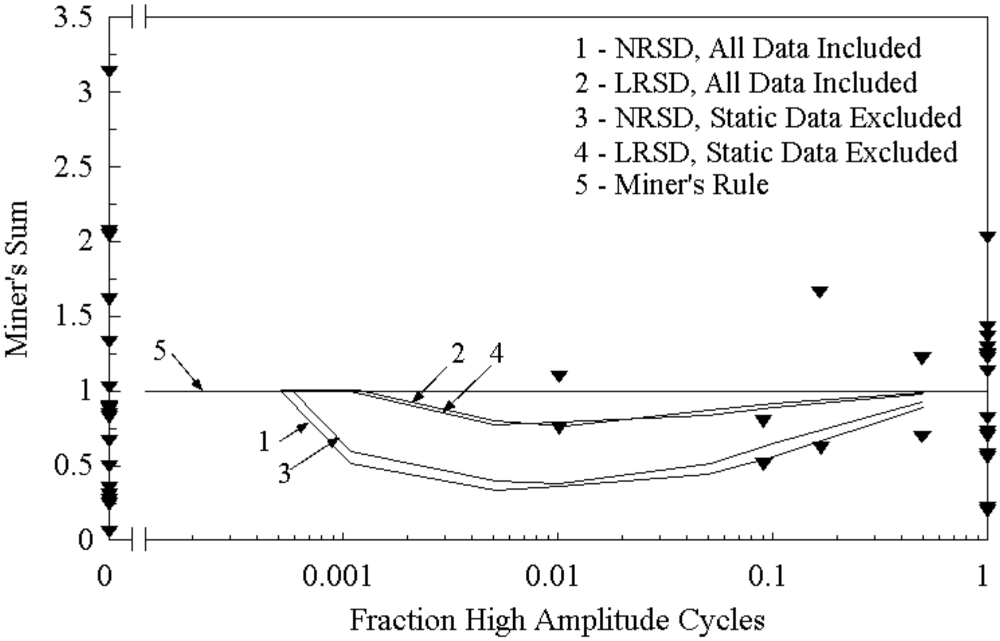


Figure 60. Two-level block loading Test Results for R = 0.5, 414 & 325 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

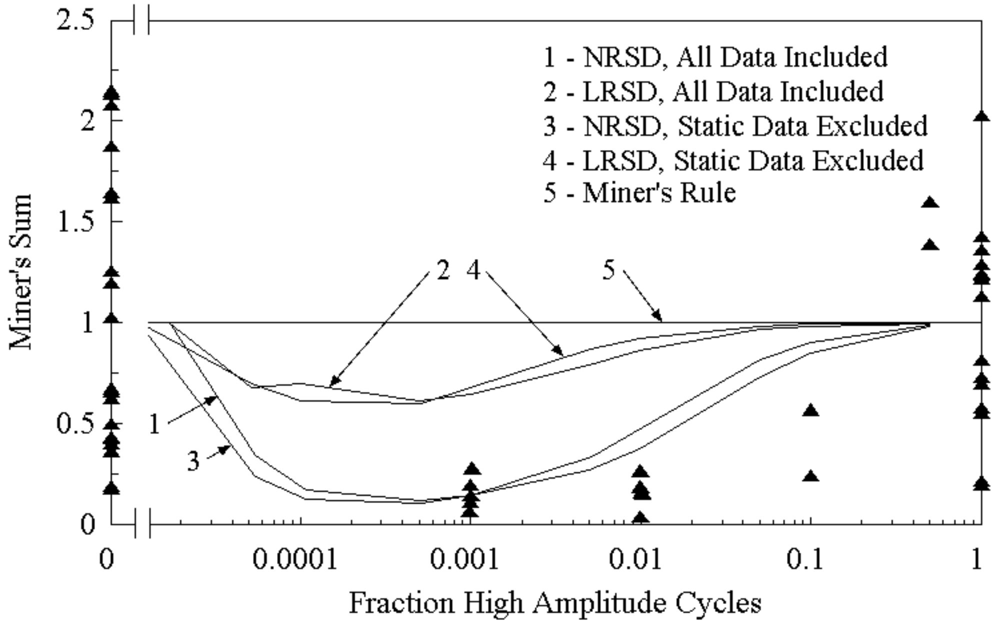


Figure 61. Two-level block loading Test Results for R = 0.5, 414 & 235 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

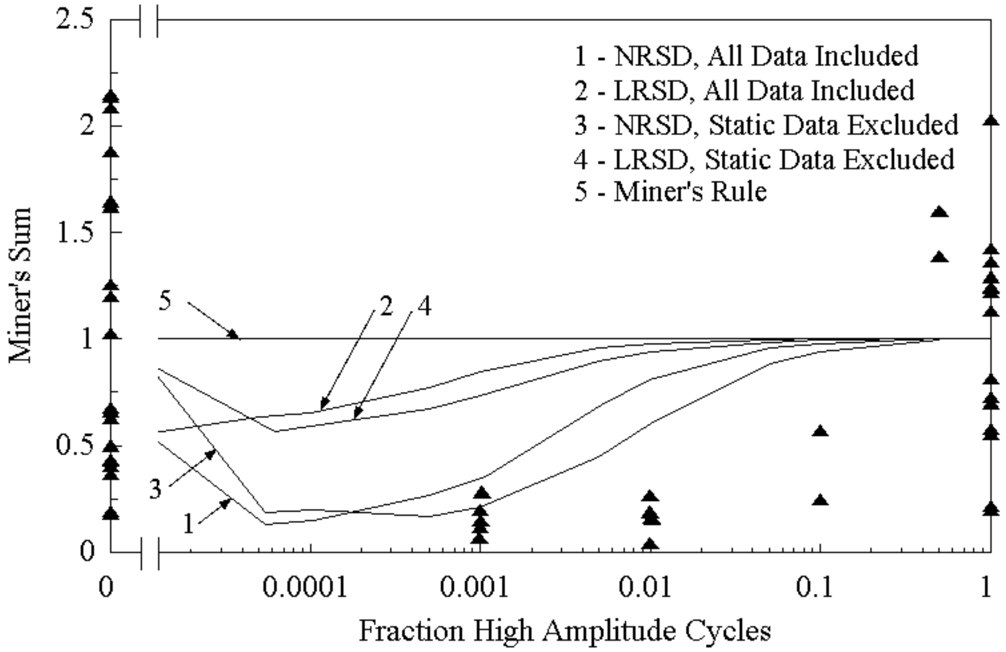


Figure 62. Two-level block loading Test Results for R = 0.5, 414 & 235 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

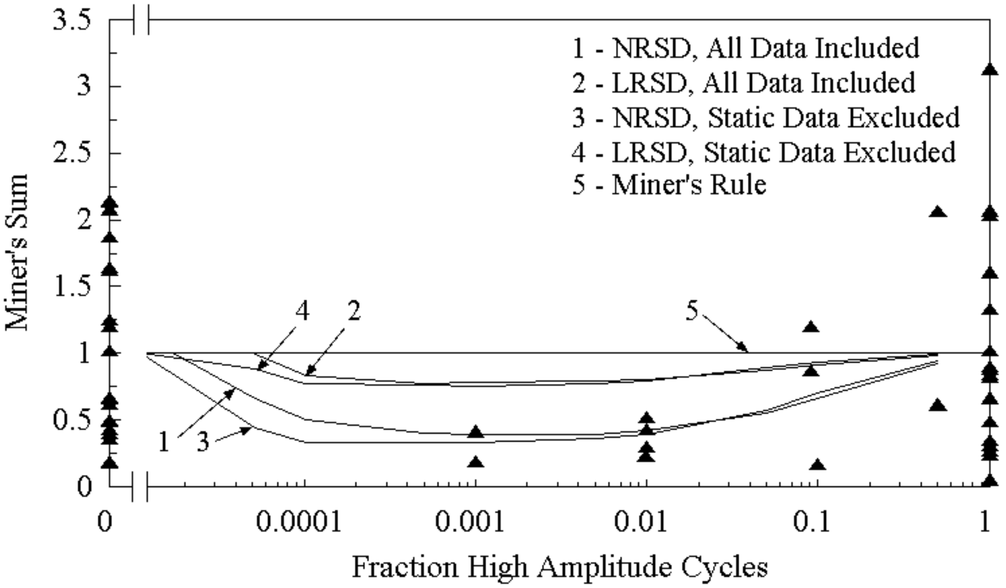


Figure 63. Two-level block loading Test Results for R = 0.5, 325 & 235 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

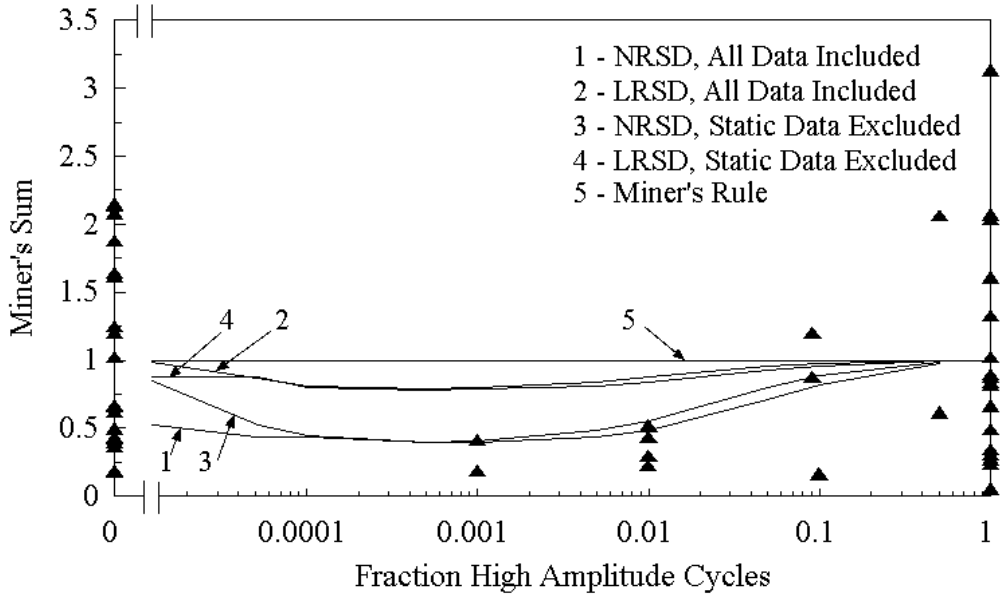


Figure 64. Two-level block loading Test Results for R = 0.5, 325 & 235 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

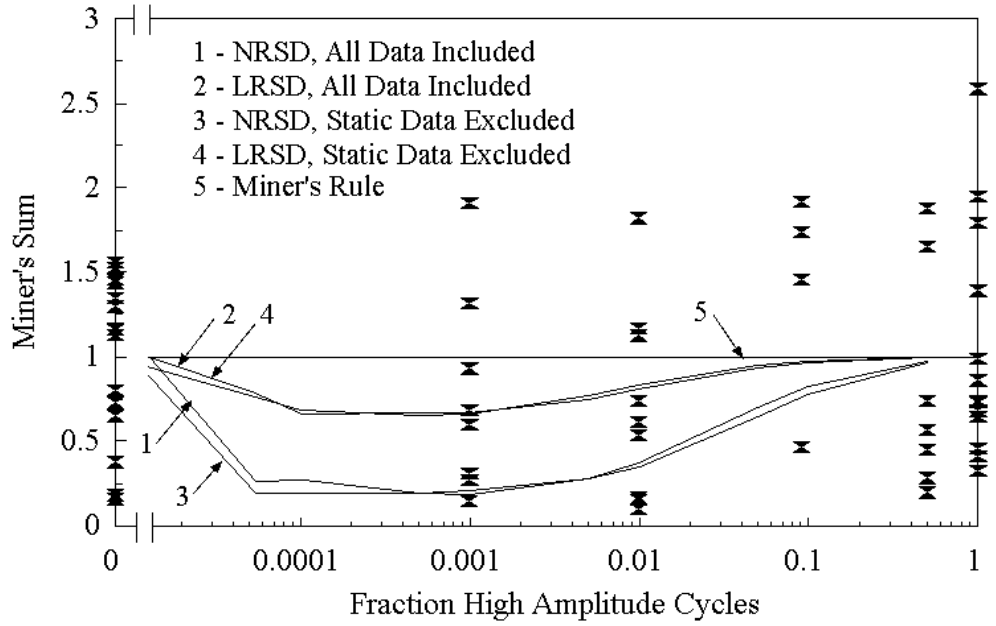


Figure 65. Two-level block loading Test Results for R = 10, -275 & -207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

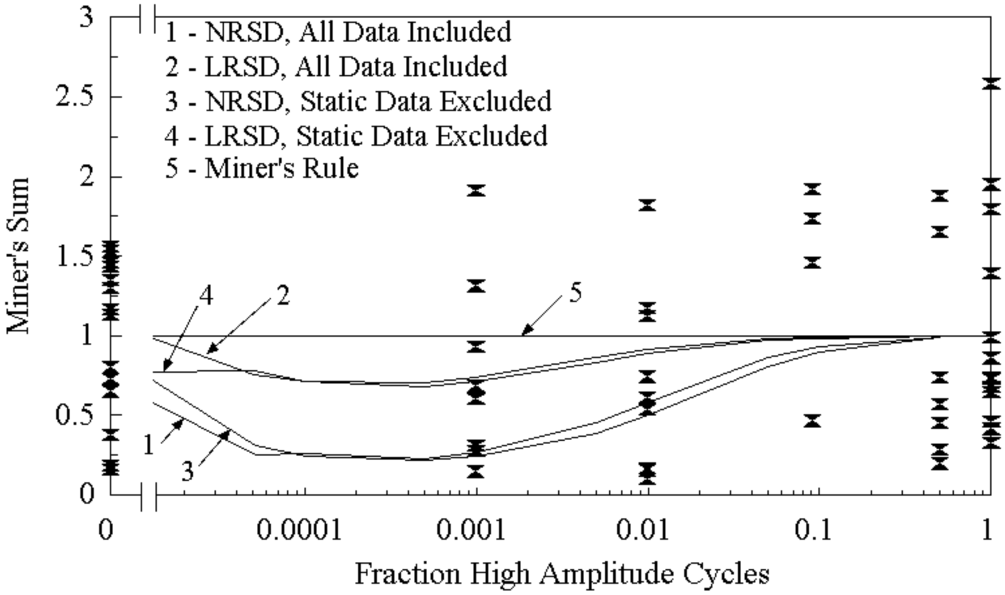


Figure 66. Two-level block loading Test Results for R = 10, -275 & -207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

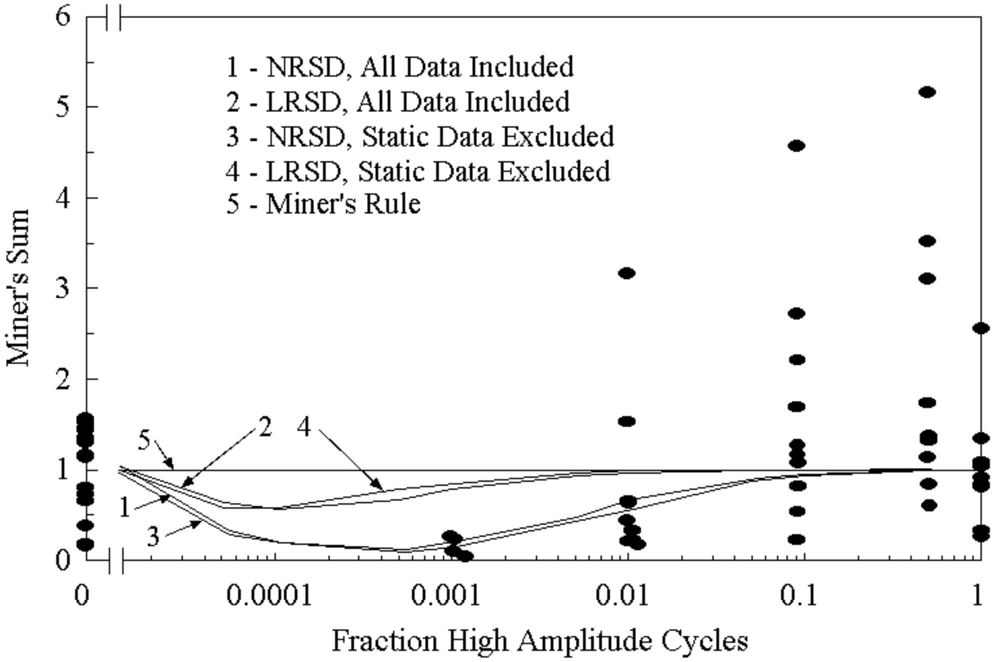


Figure 67. Two-level block loading Test Results for R = 10, -325 & -207 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner’s Rule Lifetime Predictions.

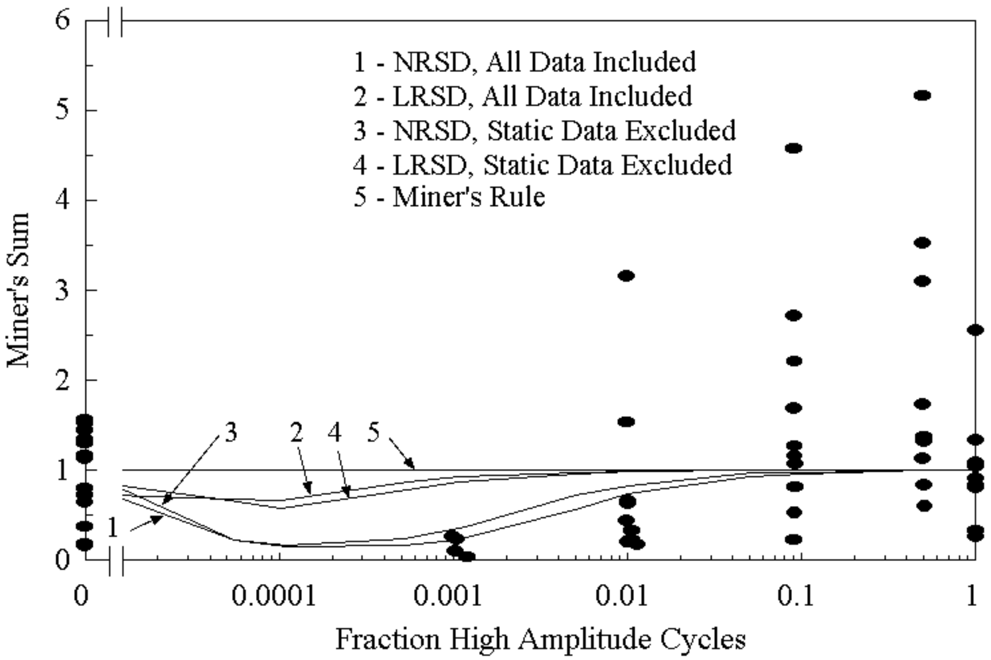


Figure 68. Two-level block loading Test Results for R = 10, -325 & -207 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Rule Lifetime Predictions.

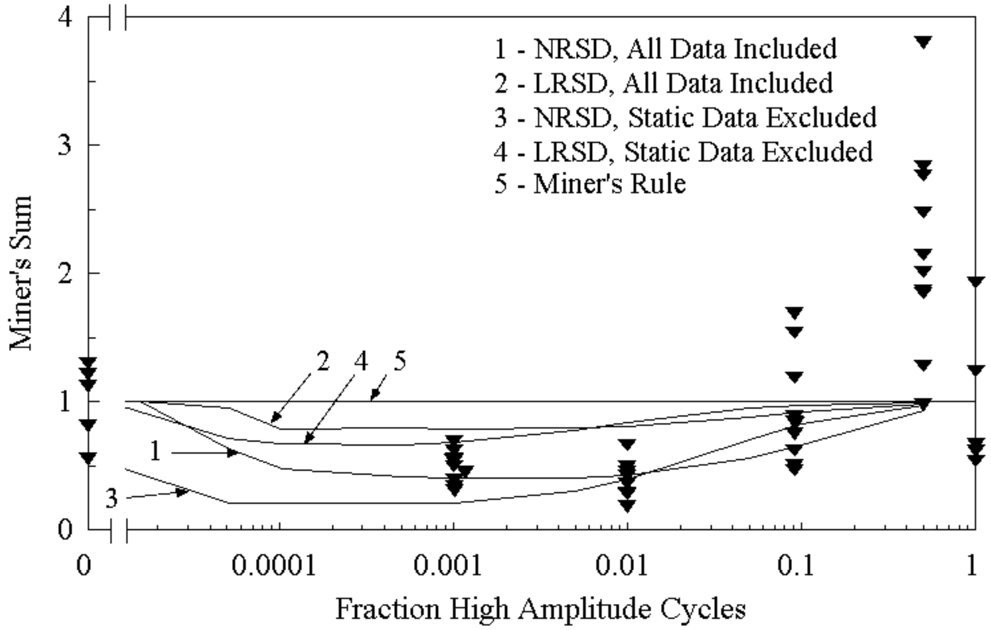


Figure 69. Two-level block loading Test Results for R = -1, 173 & 104 MPa; Exponential Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Sum Lifetime Predictions.

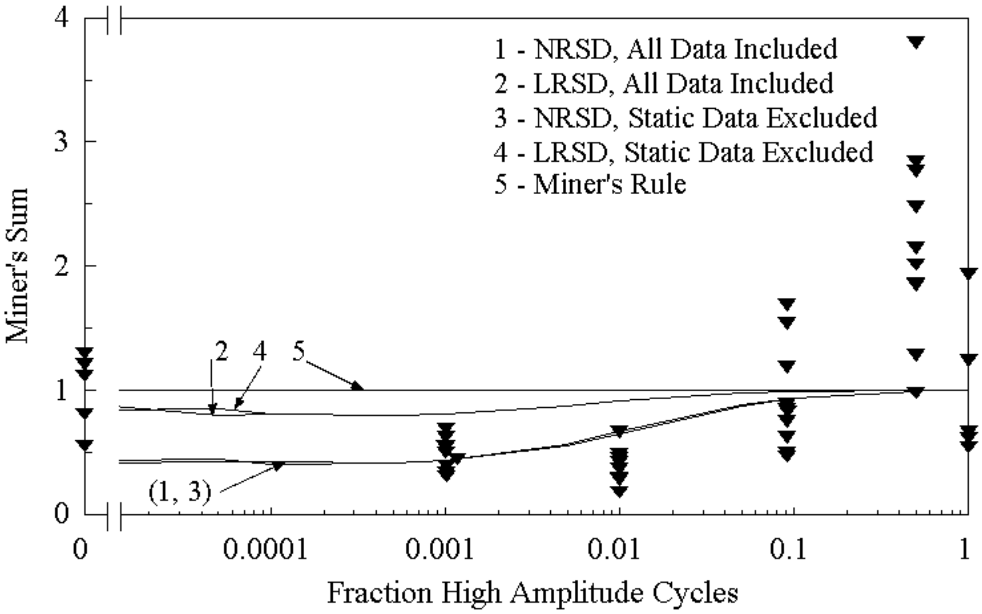


Figure 70. Two-level block loading Test Results for R = -1, 173 & 104 MPa; Power Law Fatigue Model With Linear and Nonlinear Residual Strength and Miner's Sum Lifetime Predictions.

Multi-Level Block Fatigue Testing

Additional stress levels were added to increase the complexity of the spectrum used in fatigue testing of the selected laminate. Testing of three and six level blocks was performed. The three level block test spectrum was generally comprised of ten cycles of 414 MPa maximum stress, ten cycles of 325 MPa, and 100 cycles of 235 MPa, all at an R-value of 0.1. The sequencing of the blocks was varied. Testing results were summarized and are shown in Table 7.

The six level block spectrum was arranged to the same format as that used by Echtermeyer, et. al., [50] and summarized in Table 8. Results of the six block testing are summarized in Table 9. Note, not all tests were conducted at the same maximum stress level.

The actual lifetime for each of the two, three and six level block fatigue tests will be compared to the results of lifetime prediction models in a following section. The actual Miner's sums for each of these multi-block tests were less than one.

Table 7. Three-Block Test Results

Test Number	Block Cycles	Stress MPa	Actual Cycles to Specimen Failure	Miner’s Sum at Failure
179	10	414	62	0.520
	100	325	600	
	1000	235	6000	
489	10	414	113	0.421
	10	325	110	
	100	235	1100	
490	10	325	180	0.653
	10	414	174	
	100	235	1700	
491	100	235	1600	0.576
	10	325	160	
	10	414	153	
492	10	414	123	0.458
	10	325	120	
	100	235	1200	
493	100	235	1634	0.599
	10	325	160	
	10	414	160	

Table 8. Six-Block Spectrum

Block #	Block Cycles	% Maximum Stress
1	1000	30
2	1000	50
3	400	75
4	10	100
5	400	75
6	1000	50

Table 9. Six-Block Test Results

Test Number	Block Cycles	Stress MPa	Actual Cycles to Specimen Failure	Miner's Sum at Failure
220	1000	97.5	26000	0.397
	1000	162.5	26000	
	400	243.75	10400	
	10	325	260	
	400	243.75	10337	
	1000	162.5	25000	
221	1000	103.5	8000	0.773
	1000	172.5	8000	
	400	258.75	3044	
	10	345	70	
	400	258.75	2800	
	1000	172.5	7000	
222	1000	124.2	2000	0.181
	1000	207	2000	
	400	310.5	654	
	10	414	10	
	400	310.5	400	
	1000	207	1000	
225	1000	103.5	5000	0.115
	1000	172.5	5000	
	400	258.75	2000	
	10	345	50	
	400	258.75	1857	
	1000	172.5	4000	
226	1000	82.8	48000	0.203
	1000	138	48000	
	400	207	19200	
	10	276	480	
	400	207	18968	
	1000	138	47000	

VARIABLE AMPLITUDE SPECTRUM FATIGUE TESTING AND RESULTS

Fatigue testing of the selected laminate has covered constant amplitude and block spectra in the preceding sections. As loading of wind turbine blades is more random in nature, more random spectra also must be considered. Researchers in various industries have developed standard spectra for testing [4, 16, 17]. The European wind research community developed WISPER (WInd turbine reference SPEctRum), a standardized variable amplitude loading history for wind turbine blades. Variations of this spectrum were created for use in this research.

WISPER and WISPERX

WISPER was developed from loading data collected from the root area of wind turbine blades. The out-of-plane, or flap, loading was collected from nine horizontal axis wind turbines located in western Europe. The data were distilled into a sequence of 265,423 loading reversal points, or approximately 130,000 cycles. The reversal data are normalized to a maximum of 64 and a minimum of 1. In this form, the zero load level occurs at 25.

Analysis of WISPER revealed the spectrum has an average R-value of 0.4. The single largest peak and the single most extreme valley have an R-value of -0.67. The R-value for the adjacent largest spread between the peak and valley was -2.0.

Since the application of the WISPER spectrum at 10 Hertz would take nearly four hours to make one pass, the authors of WISPER derived a shortened version to speed fatigue testing. The shortened version was created by filtering the smaller amplitude cycles, which resulted in one-tenth of the number of cycles, see Figure 71. Consequently the name applied to the new spectrum was WISPERX, the X representing the significance of the one-tenth size. Of the approximately 13,000 cycles in the WISPERX spectrum, only 143 have negative R-ratios.

The WISPER authors list several purposes [17] for the standard spectrum, including the evaluation of component design and the “assessment of models for the prediction of fatigue and crack propagation life by calculation, like Miner’s Rule.” The latter of these purposes was applied in this research.

WISPERX Modifications

WISPERX was re-scaled from its normalized form to a form compatible with the Instron software, RANDOM. The results are shown in Figure 72. The scaling followed the Equation:

$$y = \frac{[x - 25]}{[64 - 25]} \tag{18}$$

where x are the published values for the reversal points and y is the scaled version. The convenience of forcing the spectrum reversal points to a maximum of one allowed the application of any maximum stress level by a simple multiplier of value equal to the maximum stress level. Each value was saved in a format of sign (±) and the value to four significant figures (+#.####).

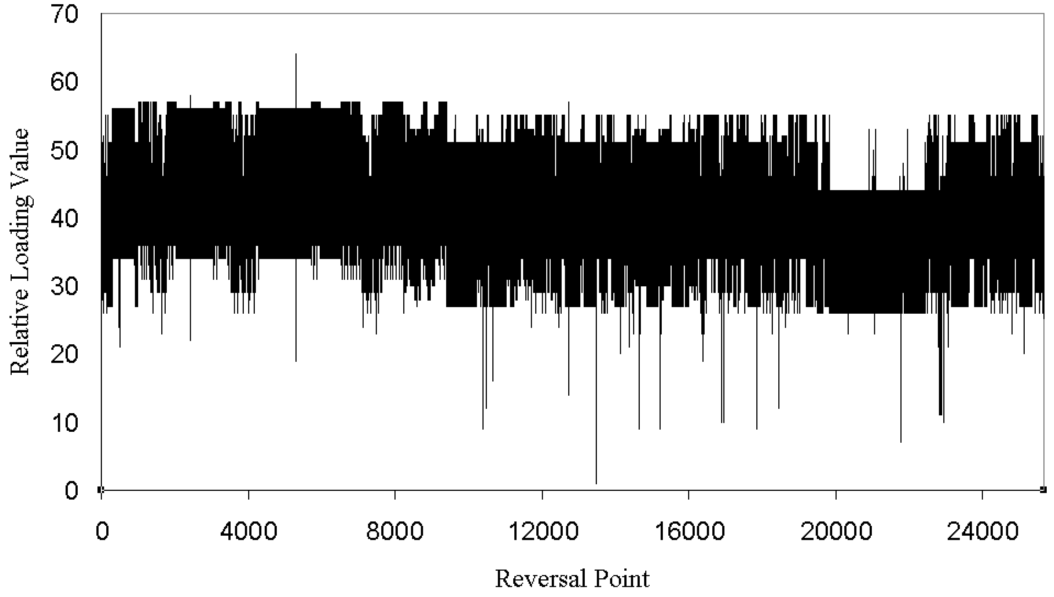


Figure 71. WISPERX Spectrum.

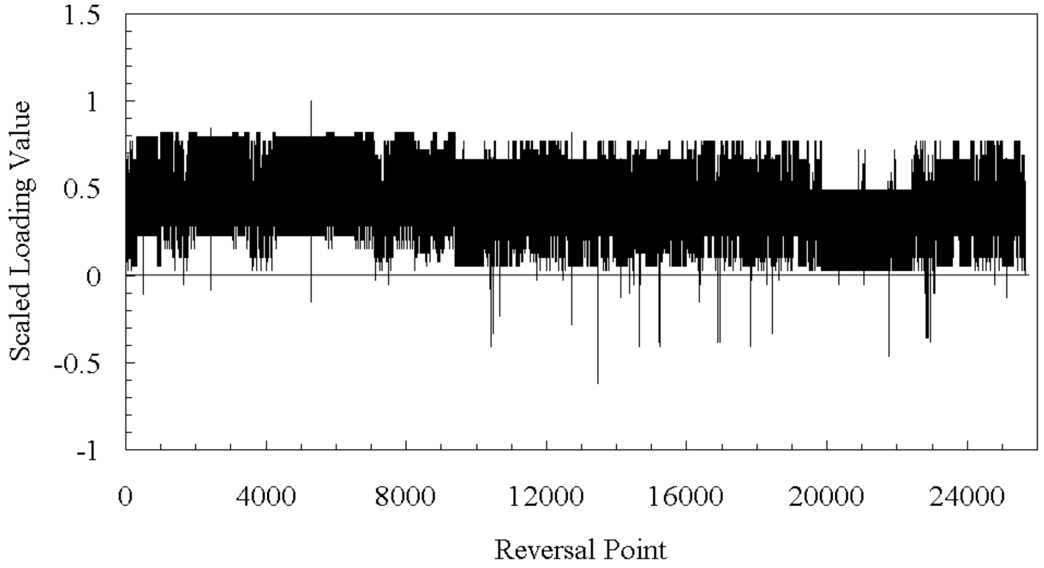


Figure 72. Scaled WISPERX Spectrum.

A wide range of R-values are present in WISPERX, yet only five R-values, other than the ultimate strengths, were tested in preparation of the base-line data. As a first step in applying this type of complex spectrum, it was decided to modify WISPERX to a constant R-value, thus avoiding both complex failure mode interactions and the need to interpolate between different R-values in the Goodman diagram. Two spectra were prepared, one for an R-value of 0.1 and one for 0.5. These modifications were accomplished by noting the peak reversal point and forcing the following valley (or trough) value to be either 0.1 or 0.5 times the peak value. A graphical version of these modifications is shown in Figure 73.

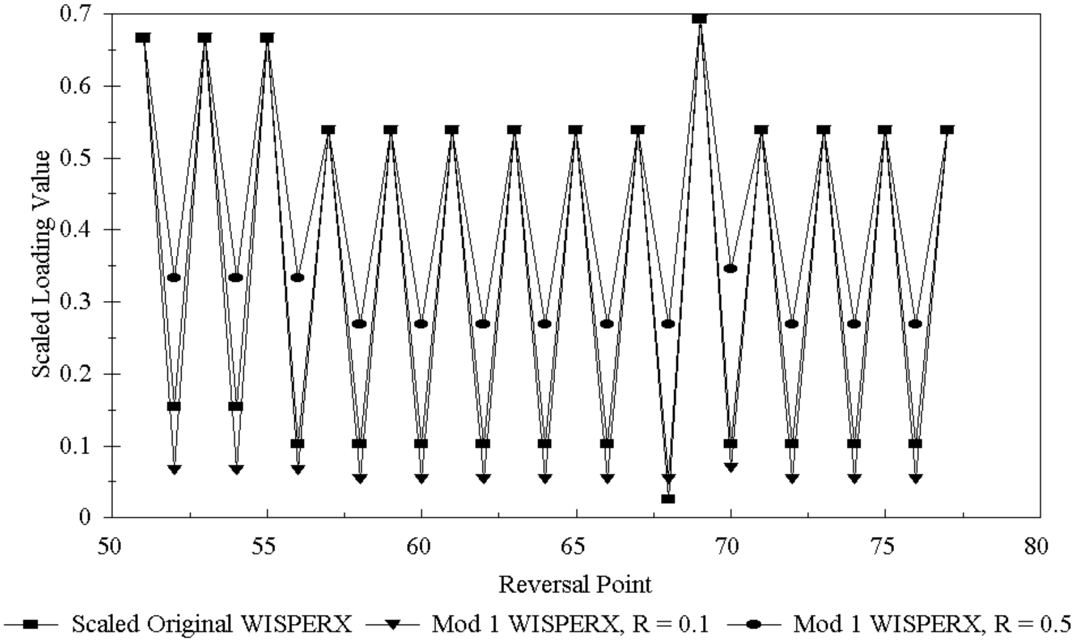


Figure 73. Modified WISPERX Spectrum Example.

Two forms of the modified spectrum were created, both forced the constant R-values, but the first, termed Mod 1, retained only the tension-tension peak-valley reversal points, while the second, Mod 2, retained all reversal points. The first spectrum did not contain the one time extreme condition that was in the original WISPER and WISPERX spectra, while Mod 2 retained this one-time high-load event. Visual appreciation of these spectra can be gained from Figures 74, 75 and 76. Note the single relatively large event occurring at approximately the 5000th reversal point in the Mod 2 spectrum, Figure 76.

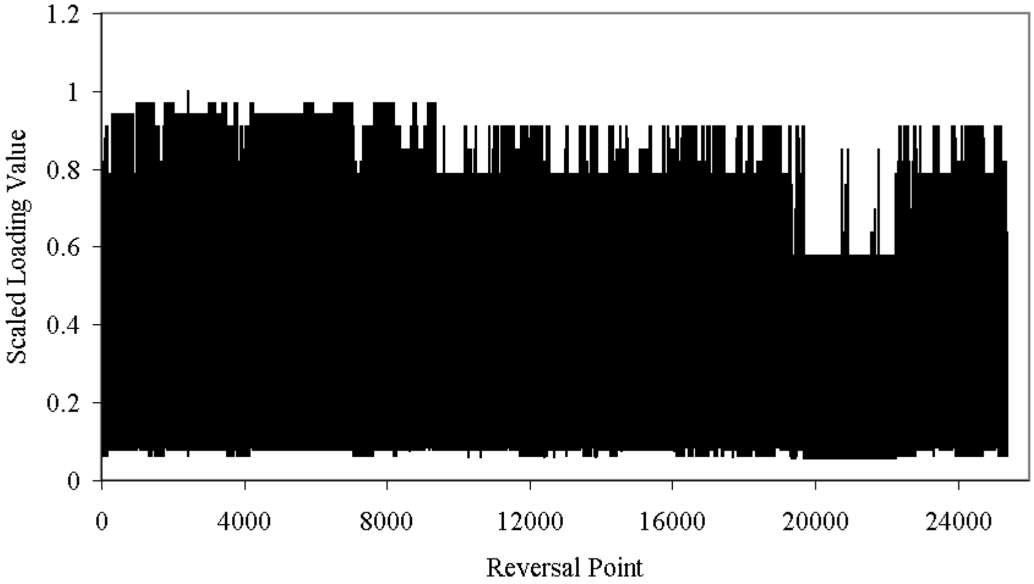


Figure 74. Mod 1 Spectrum for R = 0.1.

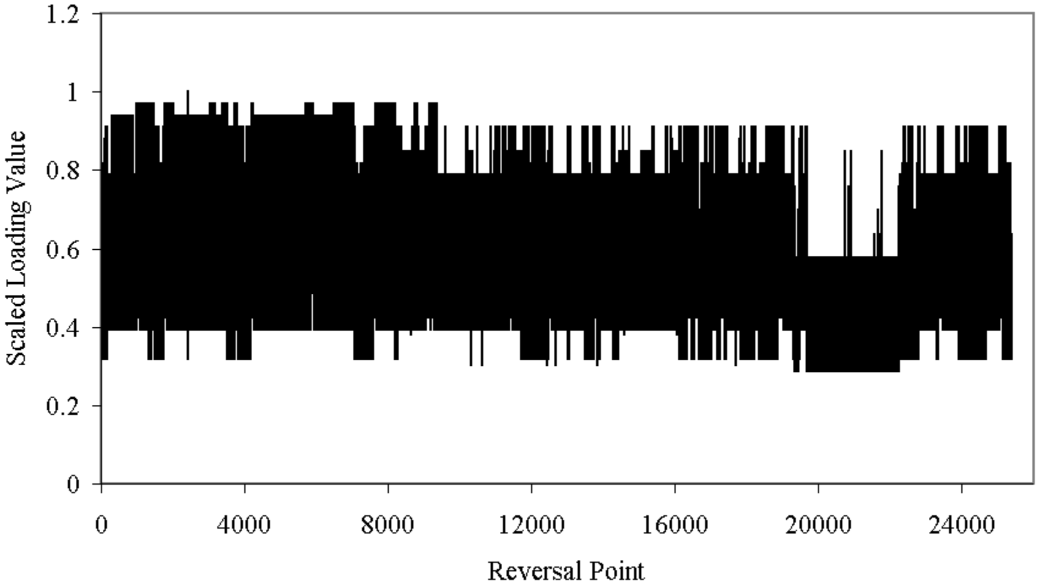


Figure 75. Mod 1 Spectrum for R = 0.5.

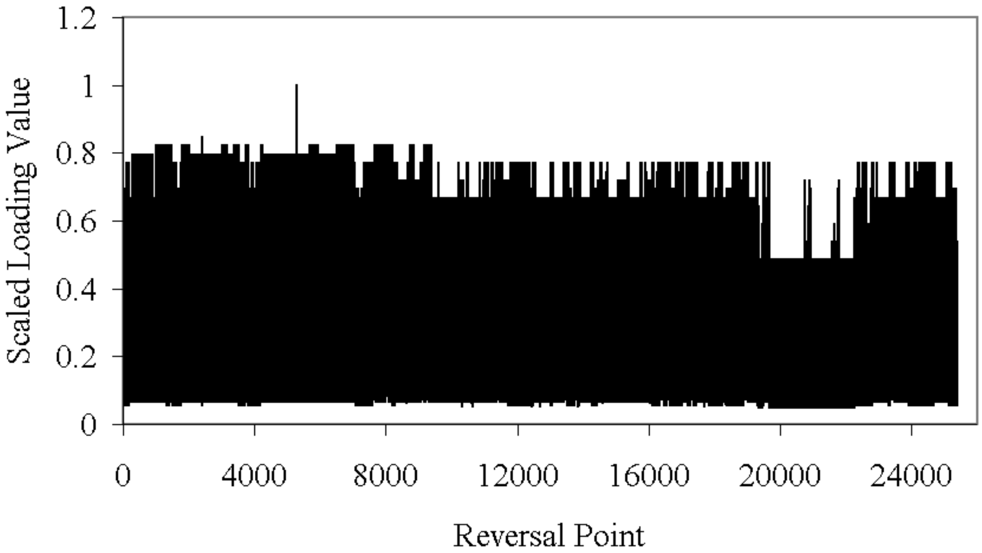


Figure 76. Mod 2 Spectrum for R = 0.1.

Modified WISPERX Spectrum Test Results

Tests were run for these spectra with the loads taken as a multiples of the scaled values. The data are then represented in conventional S-N format where the stress coordinate is the maximum stress in the spectrum. The multiplier is varied to achieve relatively higher or lower stress cases having shorter or longer lifetimes, respectively.

The results for the Mod 1 and 2 spectra are summarized in Figures 77, 78 and 79. The trend of longer lifetimes for the R-value case of 0.5 were also experienced in the constant amplitude testing. Some high stress cases fail prior to completing one full pass through the spectrum. Tables 10 and 11 include a summary of the regression parameters for WISPERX test results for the exponential and power law regression analyses, respectively. These can be compared to the constant amplitude regression results presented in Tables 4 and 5. Reference Equations 7 and 8 for definition of the terms C_1, b, C_2 and m. For reference, approximately 13,000 cycles is equivalent to one block of the WISPERX spectra. (When the static strength data were included in the curve fit, they were taken as occurring at the first cycle of the first block.)

Table 10. Exponential Regression Analysis Parameters for WISPERX Fatigue

Range of Applicability	Regression Coefficients	Spectrum			
		Mod 1, R=0.1	Mod 1, R =0.5	Mod 2, R = 0.1	WISPERX
1 to 10^7 Cycles	C_1	1.007	1.019	1.015	1.029
	b	0.121	0.107	0.106	0.107
10 to 10^7 Cycles	C_1	0.879	0.941	0.891	0.872
	b	0.094	0.091	0.093	0.079

Table 11. Power Law Regression Analysis Parameters for WISPERX Fatigue

Range of Applicability	Regression Coefficients	Spectrum			
		Mod 1, R=0.1	Mod 1, R =0.5	Mod 2, R = 0.1	WISPERX
1 to 10^7 Cycles	C_2	1.048	1.056	1.075	1.041
	m	12.02	14.52	13.9	14.2
10 to 10^7 Cycles	C_2	1.111	1.179	1.126	1.21
	m	11.28	12.72	13.1	12.2

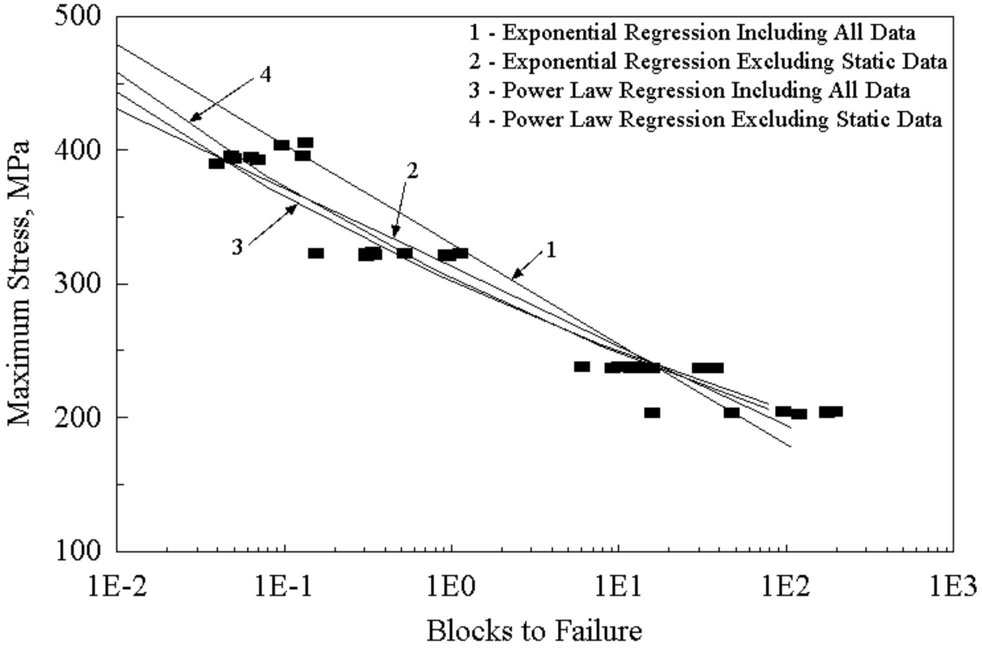


Figure 77. Mod 1 Spectrum Fatigue S-N Curve, R = 0.1.

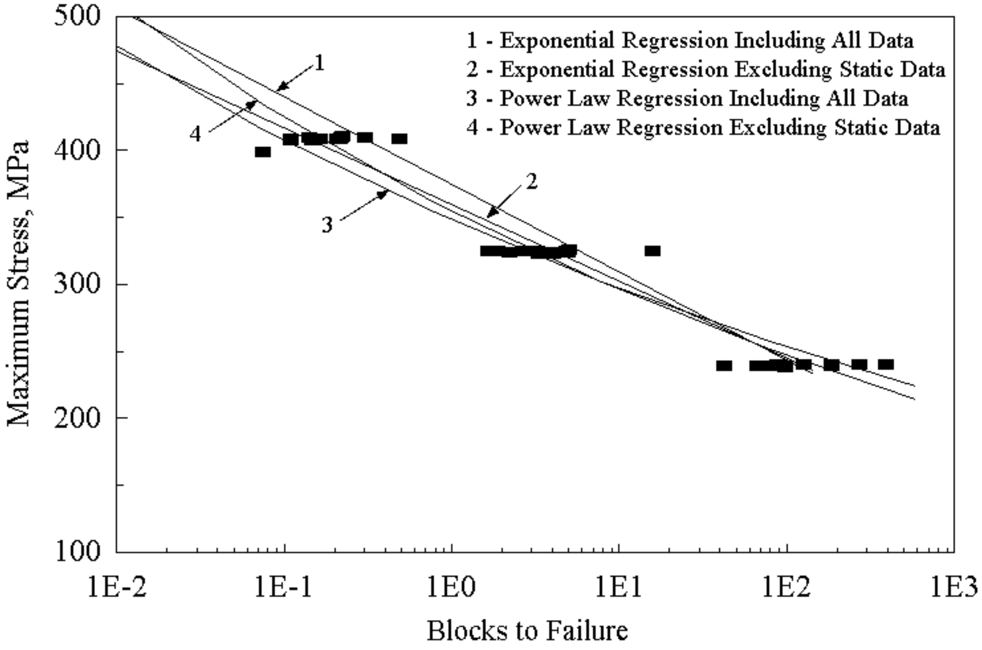


Figure 78. Mod 1 Spectrum Fatigue S-N Curve, R = 0.5.

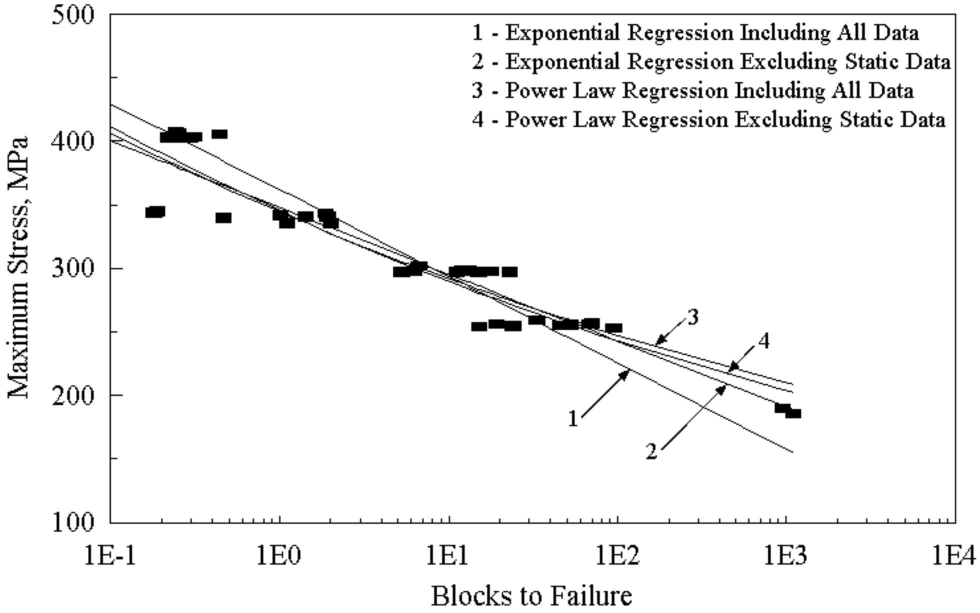


Figure 79. Mod 2 Spectrum Fatigue S-N Curve, R = 0.1.

The slope or trend of the S-N curve in the Mod 2 case is less than that of the comparable case for the Mod 1 spectrum results. The maximum stress incurred in the Mod 2 spectrum tests was a once per pass event, while the maximum stress incurred in the Mod 1 spectrum tests was experienced several times per pass.

Unmodified WISPERX Spectrum Test Results

Testing of coupons that were subjected to the original WISPERX spectrum, without modification for R-value, was also accomplished and summarized as exponential and power law S-N curves, Figure 80. The power law regression gives only slightly better correlation than the exponential regression. The regression analysis may be reviewed in Appendix D.

The actual lifetime for the random tests will be compared to the results of lifetime prediction models in the next section.

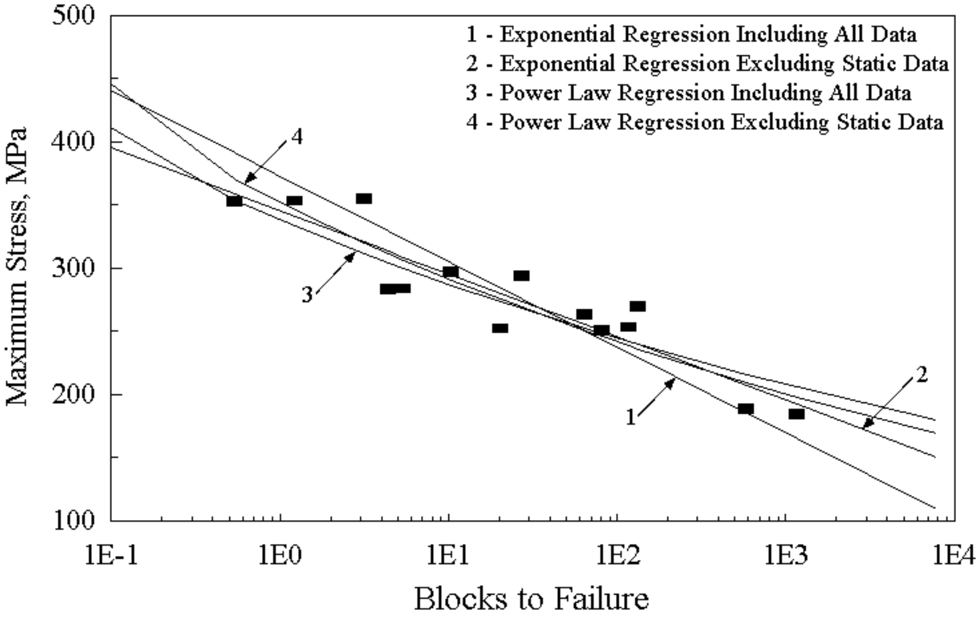


Figure 80. Unmodified WISPERX Spectrum Fatigue S-N Curve.

LIFETIME PREDICTIONS

An accurate cumulative damage law is essential to efficient component design under fatigue loading. The fundamental and most widely applied damage law is that established by Palmgren [22] and Miner [6]. Under this law, damage is considered to develop linearly as a function of the number of cycles encountered at specific load levels. As reported earlier, Miner's sum is usually less than unity, often on the order of 0.1, for tests in this study using variable amplitude loads.

A component or specimen is considered to have failed when it can no longer support the load intended. One clear deficiency in Miner's sum is that it only accumulates damage and does not consider that the current strength may be exceeded by a particular high stress cycle, whereas residual strength based models inherently consider this event. Three models have been applied to lifetime predictions for theoretical specimens subjected to the various block and modified WISPERX spectra. Results of these predictions are compared to the actual lifetimes encountered during the testing. The three models considered are, 1) Miner's Rule, 2) linear residual strength degradation, and 3) nonlinear residual strength degradation. Constant amplitude fatigue models based upon exponential and power law regression analyses as well as the retention and omission of the static data were used in the residual strength based lifetime prediction rules. All results of predictions are reported in Miner's sum and compared to the actual Miner's sums from test results.

Constant Amplitude Fatigue Life Variability

The base-line data of the constant amplitude testing was the starting point for the creation of lifetime predictions. The mean number of cycles to failure at each constant amplitude load level was used in all subsequent lifetime predictions; this would force the constant amplitude test Miner's sums to an average value of one. Using either the linear or nonlinear residual strength lifetime prediction models for a constant amplitude test would reveal the same results as Miner's rule. Note the Equations for the two residual strength degradation prediction methods, Equations 13 and 14. Failure would be predicted by either of these Equations when the residual strength was reduced to a level equivalent to the applied stress. This would happen when the number of cycles experienced, n, was equal to the number of cycles to failure, N, at that stress level. The constant amplitude test Miner's sum results are presented in Table 12. The "scatter" of Miner's sum for constant amplitude fatigue tests is greater than that experienced with metals.

Table 12. Descriptive Statistics for Constant Amplitude Miner's Sum

Case	Mean	Standard Deviation
414 MPa, R = 0.1	1	0.631
327 MPa, R = 0.1	1	0.692
245 MPa, r = 0.1	1	0.682
207 MPa, R = 0.1	1	0.644
414 MPa, R = 0.5	1	0.486
327 MPa, R = 0.5	1	0.820
25 MPa, R = 0.5	1	0.840
-325 MPa, R = 10	1	0.638
-275 MPa, R = 10	1	0.681
-245 MPa, R = 10	1	1.942
-207 MPa, R = 10	1	0.484
-275 MPa, R = 2	1	1.686
173 MPa, R = -1	1	0.591
145 MPa, R = -1	1	0.281
104 MPa, R = -1	1	0.309

Block Spectrum Fatigue Life Prediction Mechanics

Miner’s Rule Lifetime Prediction Methodology

Miner’s rule predictions are easily accomplished by accumulating the sums of each cycle ratio for each cycle of each block and repeating the sequence of blocks until this sum reaches unity. The cycle ratio for each cycle would be one (i.e. the single cycle) divided by the average number of cycles to failure at that cycle’s stress level. This method is summarized in Figure 81.

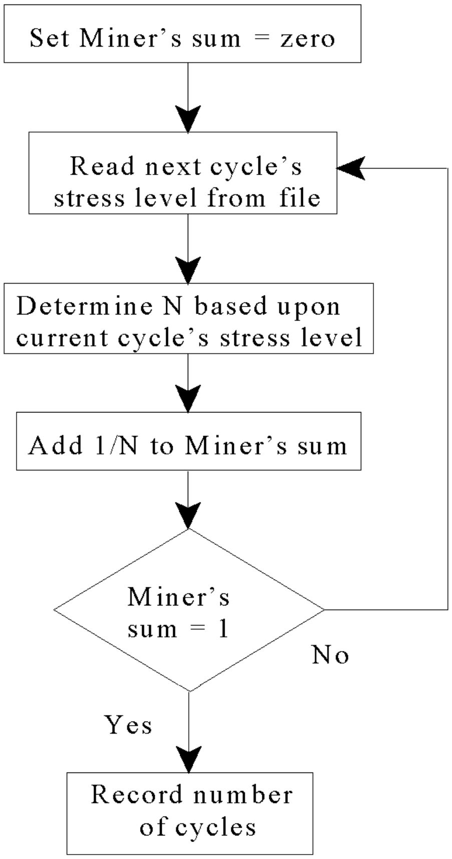


Figure 81.Miner’s Sum Lifetime Prediction Methodology.

Residual Strength Rule Based Lifetime Prediction Methodology

Consider a life prediction based upon the linear residual strength model for a two block fatigue spectrum where the first block is n_1 cycles long at a high stress level. The second block at a lower stress level is n_2 cycles long. Trace the strength through the application of a succession of blocks as shown in Figure 82.

Starting with the ultimate strength, the strength decreases monotonically with each cycle in the first block until strength, s_1, is reached after n_1 cycles of high stress. The residual strength s_1 would be the starting strength for fatigue at the stress level of the second block. The corresponding number of cycles theoretically experienced at this strength, s_1, would be n_2'. Fatigue for n_2 cycles in the second block would extend the theoretically experienced cycles from n_2' to n_2'' where $n_2'' - n_2' = n_2$, the number of cycles in the second block. The residual strength at this point in life is s_2, which would be the starting point for the next block, a repeat of the high stress cycle block. The corresponding number of theoretical cycles for at this stress level is n_3'. Fatigue at the high stress cycles would extend the number of cycles to n_3''. Since n_1 is the number of cycles in the first high stress block, then $n_3'' - n_3' = n_1 = n_3$. This process would continue until the residual strength reduces to a value equal to the applied stress.

The calculation process is identical for both the linear and nonlinear residual strength degradation prediction models. The process is valid for blocks as short as one cycle; hence, it is easily applied to random spectra as well as block spectra. The mechanics of these calculations were reduced to a computer algorithm to ease and speed data reduction.

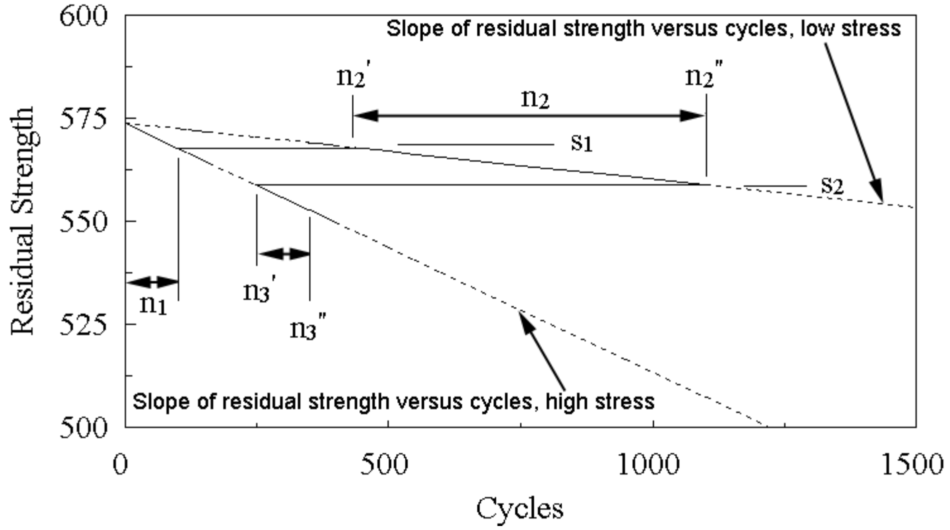


Figure 82. Lifetime Prediction Cycle Trace, Residual Strength Models.

Two-level block loading Spectrum Fatigue Life Predictions

The results of two-level block loading spectrum fatigue tests were summarized in Figures 49 through 70 as a comparison of the Miner’s sum related to the fraction of the high amplitude cycles experienced. The results of various lifetime prediction calculations were also shown on those figures. All but one of the multi-block fatigue test campaigns were performed in specific R-value regions where the mode of failure, tensile or compressive, was expected. This precluded the problem of lifetime predictions for mixed failure mode fatigue. The three prediction methods were applied in nine various configurations which are identified in Table 13 and applied for each load case.

Table 13. Lifetime Prediction Methods

1) Miner’s linear rule
2) linear residual strength based with exponential fatigue model of all data
3) linear residual strength based with exponential fatigue model excluding static data
4) linear residual strength based with power law fatigue model of all data
5) linear residual strength based with power law fatigue model excluding static data
6) nonlinear* residual strength based with exponential fatigue model of all data
7) nonlinear* residual strength based with exponential fatigue model excluding static data
8) nonlinear* residual strength based with power law fatigue model of all data
9) nonlinear* residual strength based with power law fatigue model excluding static data
* all nonlinear residual strength predictions assumed $\nu = 0.265$.

General Observations

The limit values for the fraction of high amplitude cycles for the two-level block loading tests are zero and one. A zero fraction represents a constant amplitude fatigue test conducted at the lower stress level while a fraction of one represents the results of a constant amplitude fatigue test at the higher stress level. Consequently, the average of the Miner’s sums at the limits must be one, as summarized in Table 12.

A general trend of Miner’s sums of less than one is noted in the region between fractions of zero and one. The Miner’s rule prediction is a constant value of 1.0 throughout the entire range of high amplitude cycle fractions, indicating the Miner’s rule generally predicted a longer life than observed.

The relative magnitudes of the two stress levels had an effect on the variation of the Miner's sum over the range of the high cycle fraction. Test cases that had relatively close stress levels responded with a lesser variation in the Miner's sum whereas cases with a large difference in stress levels indicated a greater variation or dip in the Miner's sum. The former observation is logical when considering the limiting case of equal stress levels for each block. This would be a constant amplitude fatigue case for which the Miner's sum would be 1.0.

Comparison of Residual Strength Based Lifetime Prediction Rules

The nonlinear rule with $\nu = 0.265$ consistently provided Miner's sums less than those predicted by the linear residual strength degradation rule. This was assured by choosing the nonlinear parameter to be less than one, thereby forcing the predictions to more closely follow test results. Choosing a nonlinear parameter greater than unity would have caused the nonlinear Miner's sums to be greater than those calculated by the linear residual strength degradation method. Both methods trend towards unity at the limits of the high cycle fraction as shown in all Figures 49 through 70. In some cases such as that of Figures 55 and 59, the prediction stabilizes at unity for a range of cycle fractions above zero. In these cases, reducing the high cycle fraction below some value was not possible in that the predicted failure was always in the second low amplitude stress block, and the first high amplitude stress block was never repeated.

The linear and nonlinear methods produce converging Miner's sum predictions when the two block stress levels become closer. Typical examples of this latter observation are those in Figures 49 and 57 for R-values of 0.1 and Figures 65 and 67 for R-values of 10.

Fatigue Model Selection Effect on Predictions

The fatigue models (Equations 7 and 8) were based upon the regression analyses of the constant amplitude fatigue test results. There were four basic models prepared: 1) exponential regression analysis that included all fatigue data for each R-value; 2) exponential regression analysis that excluded the static data; 3) power law regression analysis that included all fatigue data; and 4) power law regression analysis that excluded the static data. As there is some concern of possible differences in damage metrics that occur in high stress fatigue, including static tests, and the fatigue at lower stress levels, two fatigue models were prepared for consideration. This also allows breaking the regression results that represent the S-N fatigue data into a series of curves, each considered valid over a range of component life.

Generally, the nonlinear residual strength degradation based prediction models are sensitive to which of the four fatigue models is chosen, whereas the linear strength degradation based predictions models are insensitive. Consider Figure 26, the S-N diagram for constant amplitude fatigue at R-values of 0.1. The power law regression models for both cases of including and excluding the static data are nearly identical. This can also be seen in Figure 50 for the nonlinear lifetime predictions for the two-level block loading case of block stresses of 414 and 325 MPa with R-values of 0.1. The exponential regression models represented in Figure 28 are quite different for the cases of including and excluding the static data. At the higher cycles, an equivalent higher stress is required to cause failure for the exponential fatigue model that excludes the static data than that which includes the static data. Again, this is borne out in the predictions summarized in Figure 49, where the Miner's sums at the low cycle, high amplitude fractions are greater for the NRSD exponential fatigue model that excluded the static data than for that which included the static data.

The nonlinear residual strength based prediction rules provided better agreement with test results than did the linear based rule. Generally, the selection of the fatigue model had little influence in the predictions, at least for the cases of two-level block loading spectra. This would be expected for these cases, where extrapolation of the constant amplitude data was not required.

Three and Six-Block Spectrum Fatigue Life Predictions

The actual Miner's sums for the three and six level block tests (spectra shown in Tables 7 and 8) were consistently less than one, as summarized in Tables 14 and 15. The linear residual strength model predictions of the Miner's sum were always higher than the actual Miner's sums. The nonlinear residual strength model predictions of the Miner's sum were mostly higher than the actual.

Note the predictions for the both linear and nonlinear models are closer to the actual than what would have been predicted by Miner's rule. The nonlinear prediction is closer to the experimental value than the linear prediction in every case.

Modified WISPERX Spectra Fatigue Life Predictions

Predictions for the modified WISPERX spectra were made along the same lines as for block spectra. Predictions based on the three models were reduced to a graphical form of the S-N curve type as in Figures 83 through 88 based upon the exponential and power law fatigue models. The shape of the curves in the higher stress region has abrupt changes in slope that occur at identifiable cycles in the spectrum. The stress level increments used in the calculation of the lifetimes has an effect on the overall shape of these curves, yet the general trend can be ascertained from the presented figures. In general, the Miner's rule and the linear residual strength degradation models produce similar predictions, while the nonlinear residual strength degradation model is more conservative.

Figures 83 and 84 include the lifetime predictions for the Mod 1 WISPERX spectrum at an R-value of 0.1 for the exponential and power law fatigue models, respectively. The trend of this spectrum, shown in Figure 74, has a change in the average maximum stress level at around the 9,000th reversal point (4,500th cycle) and another at approximately the 19,000th reversal point (9,500th cycle). These are consistent with the changes in the slope in Figures 83 and 84. The scale compression of the logarithm prevents the observation of these slope changes for the higher cycle (greater number of blocks) regime. The power law fatigue model appears to provide a better correlation with the experimental data than the exponential fatigue model for the high cycle regime and for any of the three prediction models.

Table 14. Three-Block Spectrum Fatigue Life Predictions

Test Number	Sequence Cycles	Load	Actual Cycles	Miner's Sum		
				Actual	Linear Prediction	Non-Linear Prediction
179	10	414	62	0.520	0.770	0.282
	100	325	600			
	1000	235	6000			
489	10	414	113	0.421	0.920	0.657
	10	325	110			
	100	235	1100			
490	10	325	180	0.653	0.918	0.651
	10	414	174			
	100	235	1700			
491	100	235	1600	0.576	0.916	0.648
	10	325	160			
	10	414	153			
492	10	414	123	0.458	0.920	0.657
	10	325	120			
	100	235	1200			
493	100	235	1634	0.599	0.916	0.648
	10	325	160			
	10	414	160			

Table 15. Six-Block Spectrum Fatigue Life Predictions

Test No.	Sequence Cycles	Load	Actual Cycles	Miner's Sum		
				Actual	Linear Prediction	Non-Linear Prediction
220	1000	97.5	26000	0.397	0.758	0.335
	1000	162.5	26000			
	400	243.75	10400			
	10	325	260			
	400	243.75	10337			
	1000	162.5	25000			
221	1000	103.5	8000	0.173	0.747	0.296
	1000	172.5	8000			
	400	258.75	3044			
	10	345	70			
	400	258.75	2800			
	1000	172.5	7000			
222	1000	124.2	2000	0.181	0.677	0.203
	1000	207	2000			
	400	310.5	654			
	10	414	10			
	400	310.5	400			
	1000	207	1000			
225	1000	103.5	5000	0.115	0.747	0.296
	1000	172.5	5000			
	400	258.75	2000			
	10	345	50			
	400	258.75	1857			
	1000	172.5	4000			
226	1000	82.8	48000	0.203	0.814	0.406
	1000	138	48000			
	400	207	19200			
	10	276	480			
	400	207	18968			
	1000	138	47000			

Figures 85 and 86 are a summary of the lifetime predictions for the Mod 1 WISPERX spectrum at an R-value of 0.5. The general slope of these prediction curves are less than those of the same spectrum at an R-value of 0.1, as might be expected based upon the results of the constant amplitude fatigue testing. The changes in slope of the predictions are again due to changes in the load values, as evident in Figure 75 for this spectrum. There is little difference among the results for the three prediction models, although the power law fatigue model may provide a better overall correlation with the data at the high stress level. The exponential model appears to provide a better correlation at the low stress level, yet the trend at the lowest stress levels does require further investigation.

Figures 87 and 88 are the results of lifetime predictions for the Mod 2 WISPERX spectrum. The much more dramatic change in slope evident in these figures is a result of the single high load cycle present in this spectrum at approximately the 5,000th reversal point (2,500th cycle) as evident in Figure 76. In general, the lifetime predictions based upon the power law fatigue model provide better correlation with the experimental data than does the exponential fatigue model. The nonlinear strength degradation lifetime prediction method provides a closer correlation to the data than does the other two models. The greater differences in the stress levels created by the presence of the single high load cycle, seems to cause greater variability of the prediction produced by the three models.

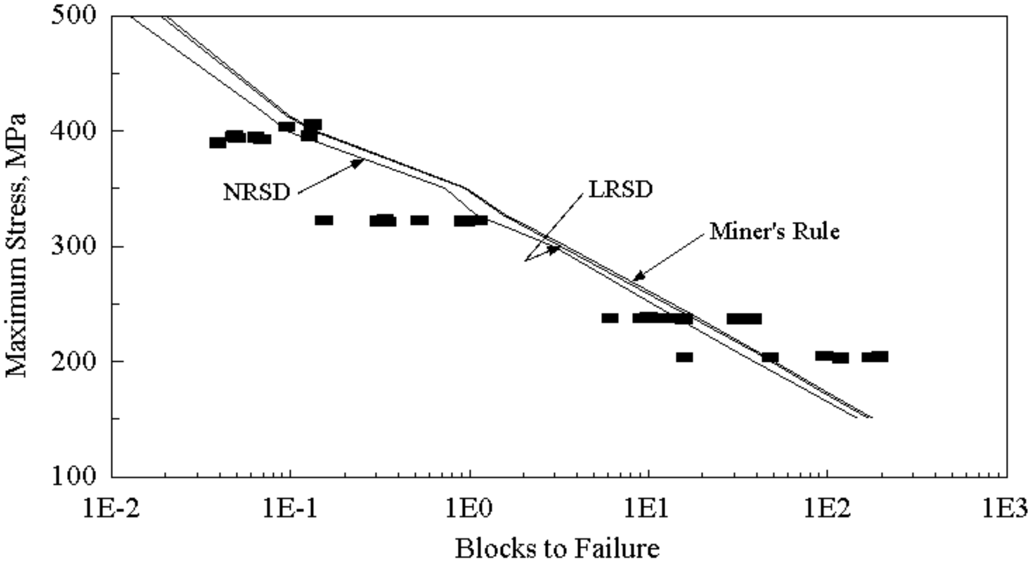


Figure 83. Mod 1 Spectrum Lifetime Predictions, R = 0.1 Exponential Fatigue Model Including All Data.

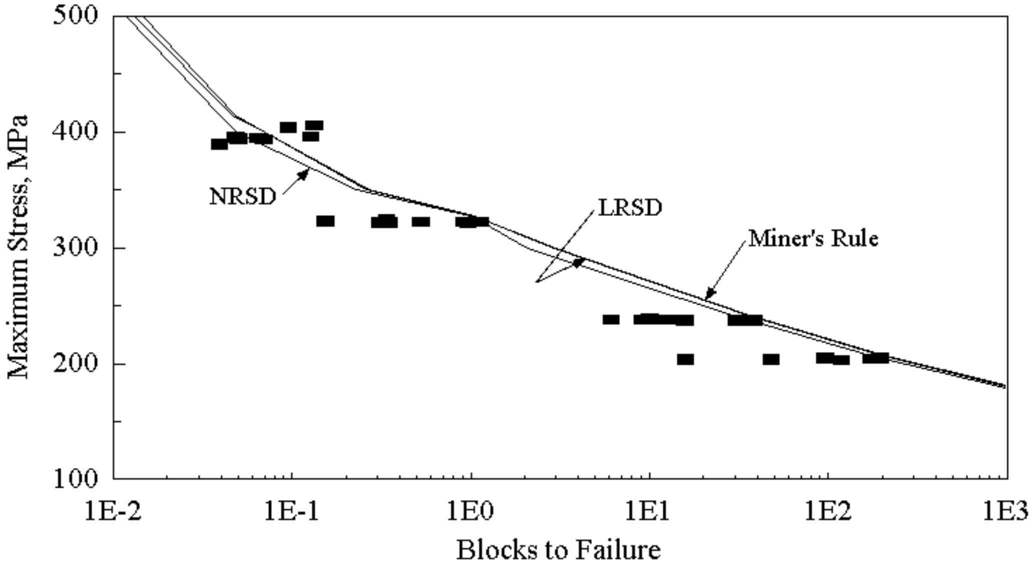


Figure 84. Mod 1 Spectrum Lifetime Predictions, R = 0.1 Power Law Fatigue Model Including All Data.

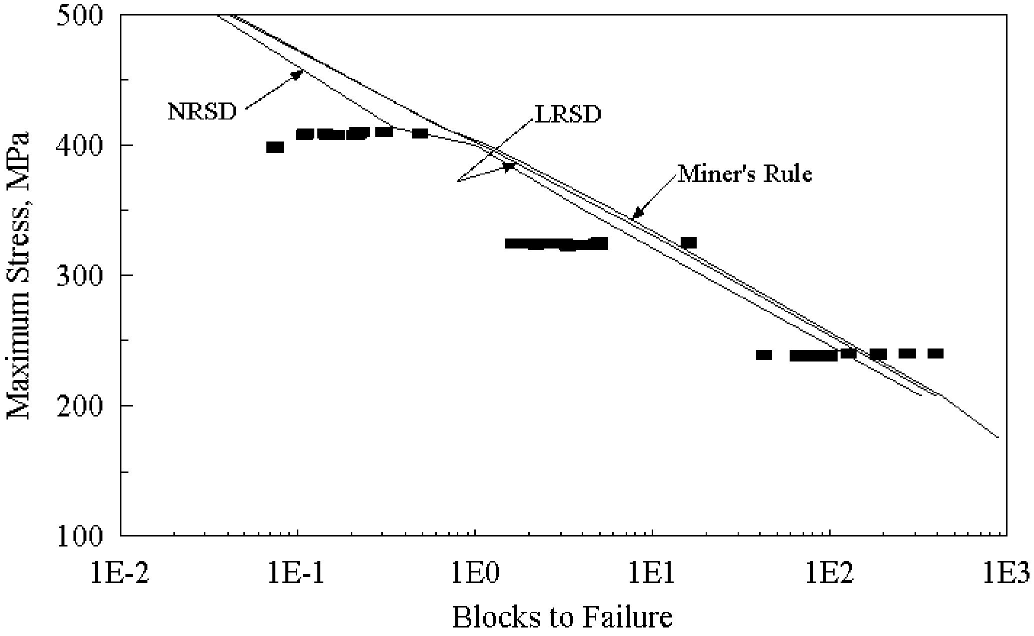


Figure 85. Mod 1 Spectrum Lifetime Predictions, R = 0.5 Exponential Fatigue Model Including All Data.

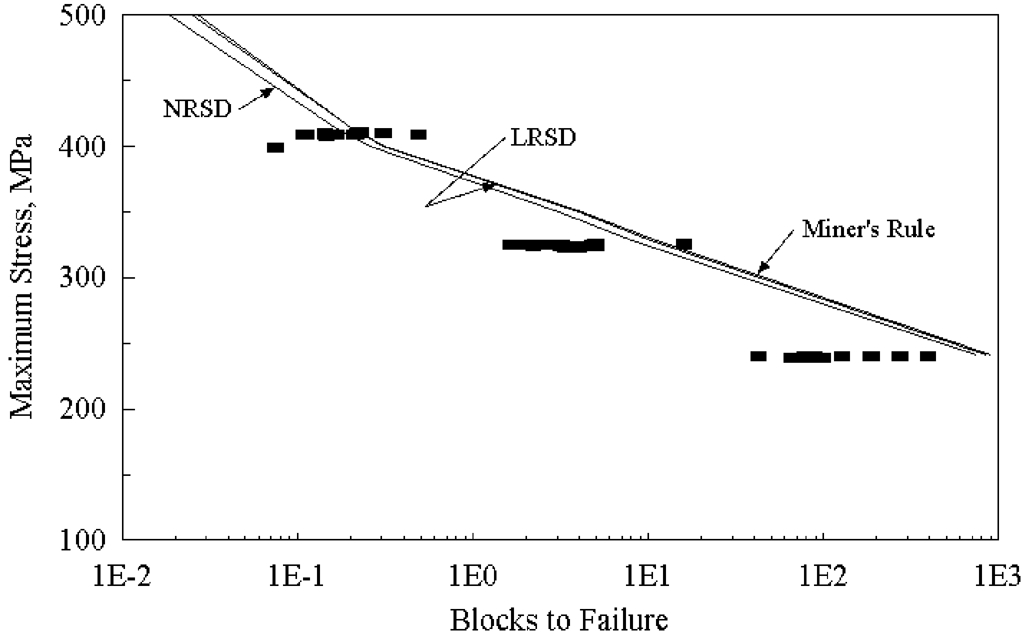


Figure 86. Mod 1 Spectrum Lifetime Predictions, R = 0.5 Power Law Fatigue Model Including All Data.

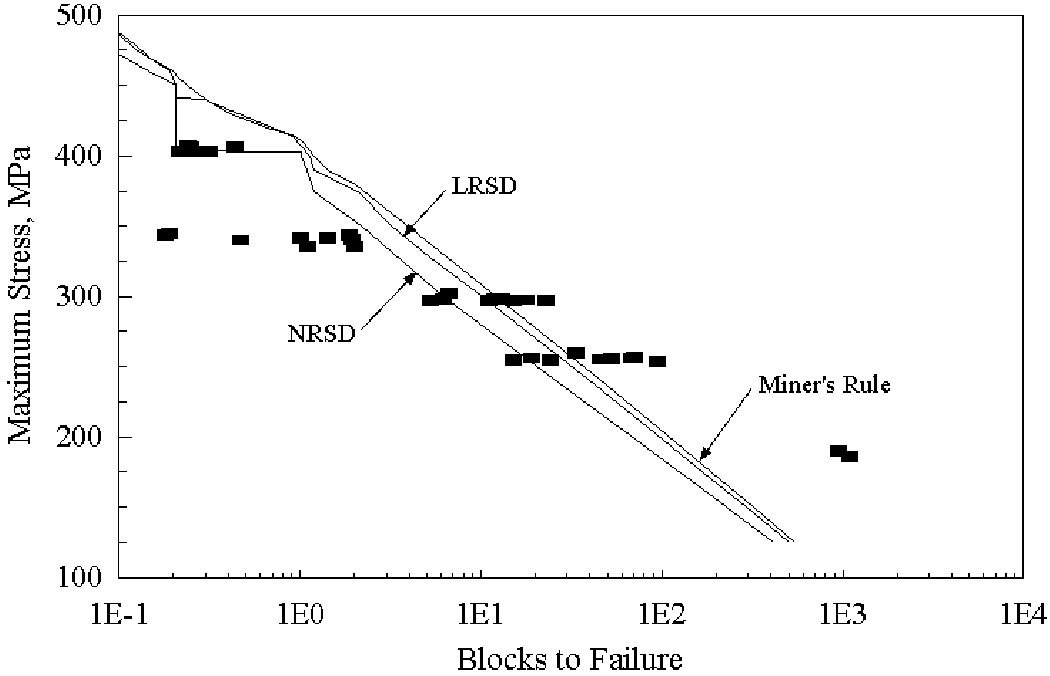


Figure 87. Mod 2 Spectrum Lifetime Predictions Exponential Fatigue Model Including All Data.

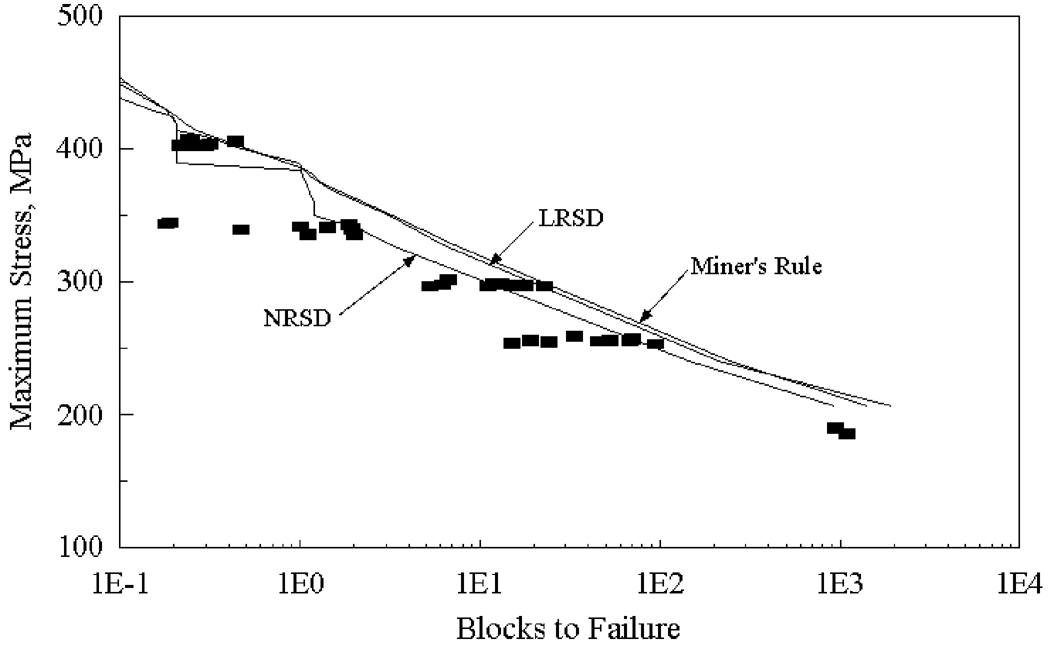


Figure 88. Mod 2 Spectrum Lifetime Predictions Power Law Fatigue Model Including All Data.

It, therefore, seems that the selection of the prediction model becomes important when the variability of the stress levels in the spectrum becomes greater, as was the case in the Mod 2 spectrum.

The choice of the fatigue model becomes important for the case of a modified WISPERX spectrum fatigue predictions at the low stress/high cycle regime, where more of the cycles are at stress levels where the constant amplitude data must be extrapolated beyond the experimental data. The power law fatigue model provides a better correlation to data.

Block or Cycle Damage Contributions

Are all stress levels important in the fatigue of the laminate, or is one set of levels more damaging than others, to the point that all other stress cycles can be ignored? If the cycle ratio (the ratio of cycles experienced to cycles to failure, Equation 3) is an indication of the damage contribution at each level, which is the premise of all three models investigated herein, then comparisons of the cycle ratio at each stress level can answer this question.

Consider the heavily tested two-level block loading case of R = 0.1 with the two maximum stress levels of 325 and 207 MPa. There were over 100 tests performed at the approximate high amplitude cycle fractional ratio of 0.01 (reference Figure 62). The average tested Miner’s sum for this case was 0.287, with a standard deviation of 0.222. Compare these statistics to the constant amplitude test results of Miner’s sums of one. The average two-level block loading Miner’s sum was considerably less than one, while the standard deviation was also less, indicating less scatter for the block testing. The average calculated damage contribution based on Miner’s sum due to the higher stress cycles was 36 percent, with the remaining 64 percent due to the low amplitude cycles. This can better be summarized graphically, Figure 89, for this cycle fraction along with the other fractions. For a spectrum with 15 percent high amplitude stress cycles, the damage contribution is split equally between the two load levels. Notice, when the high amplitude stress spectrum content was roughly 50 percent or greater, all the damage essentially could be attributed to the high amplitude cycles. In going from a spectrum of only high amplitude cycles and gradually adding low amplitude cycles, the fraction of high amplitude cycles has to be decreased to approximately half before the low amplitude cycles contribute 10% of the damage. Conversely, upon starting with a spectrum of only low amplitude cycles, the high amplitude content only needs to be increased to 0.2% before the high amplitude cycles contribute 10% of the damage.

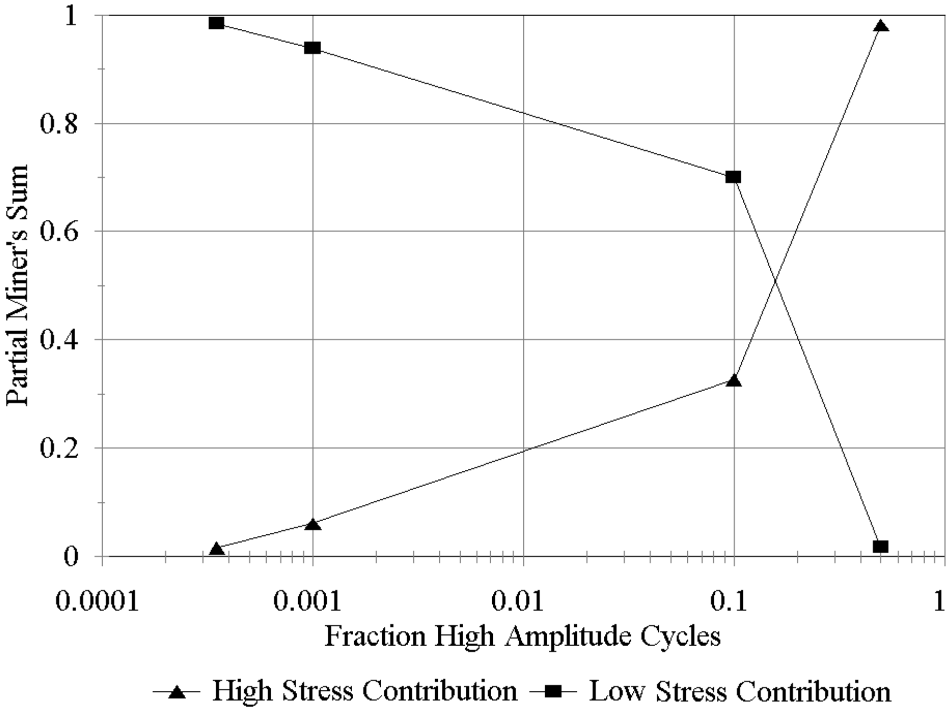


Figure 89. Two-level block loading Stress Level Damage Contributions.

Analysis of the damage contribution for the more variable spectra, such as the various modified WISPERX cases, can be done similarly, provided the stress levels are properly handled. Since there is a multitude of stress levels in the WISPERX spectrum, segregating the levels into a series of increasing groups would produce a set of manageable size. Traditionally, this grouping is accomplished by rainflow counting methods [56, 57]. Here, each stress cycle is isolated, from which the range and mean values for that cycle are calculated. A matrix of bins for each of the groupings for range and mean is filled with the count of the number of cycles in each. A computer algorithm was developed to perform the necessary calculations to rainflow count a spectrum. Figure 90, is a three dimensional representation of a rainflow count of the published WISPERX spectrum. For comparison, a rainflow count of a constant amplitude test would have a single peak at a unique bin. A rainflow count of a two-level block loading test would display two peaks at two unique bins representative of the two stress levels. The Mod 1 or Mod 2 spectrum would appear as a series of peaks formed along a straight line on the plane of a rainflow count matrix. The slope of this line would be in accordance with that of Equation 2, (1 - R)/(1 + R).

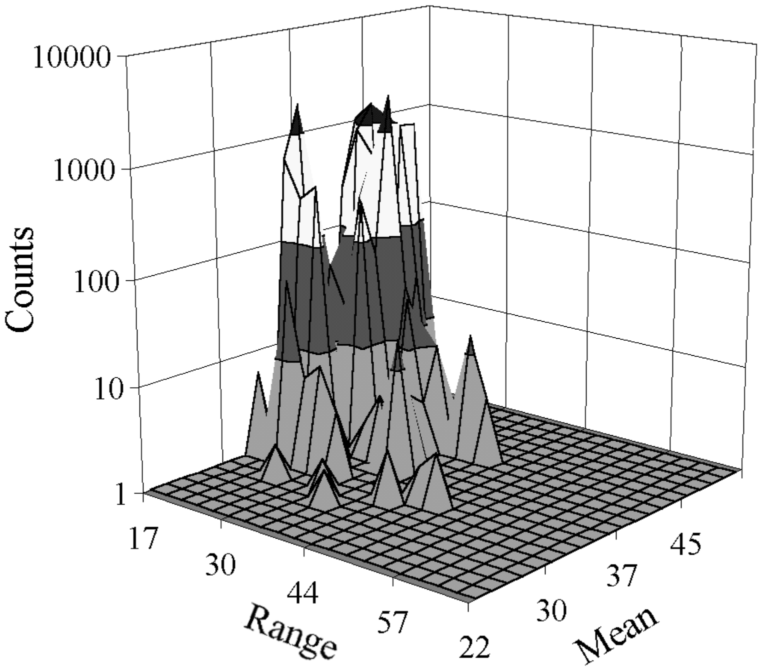


Figure 90. WISPERX Spectrum Cycle Count.

Information from a matrix such as that in Figure 90 can be used along with the fatigue models, Tables 4 or 5, to develop a Miner's sum for theoretical tests performed with the spectrum represented. The comparisons in Figures 91 and 92 use the exponential fatigue model with static data included. The damage caused by each bin of stress cycles can also be calculated, such as that shown in Figure 91. For the case shown in Figure 91, Mod 1 spectrum, R = 0.5, 414 MPa maximum stress, the relatively low number of high amplitude cycles caused the greatest amount of damage to the laminate. As the maximum stress level was decreased, the significance of the high amplitude cycles, although still significant, became less. Figure 92 displays results for a test similar to that of Figure 91, but with the maximum stress reduced.

Generally, as a spectrum includes a greater difference in load levels, the life prediction model becomes more important. This is illustrated in Figure 93, which shows predictions for two-level block loading repeated spectra with different ratios of low to high block amplitude. When the damage is mostly caused by low stresses, but occasional high stresses occur, then the residual strength models are more accurate and differ strongly from Miner's rule [58]. The 24 percent ratio is less than half of the any tested stress ratios shown in the two-level block loading figures discussed earlier. Reducing the fraction of high amplitude cycles to zero would cause the Miner's sum to trend to one, the low amplitude constant amplitude mean Miner's sum.

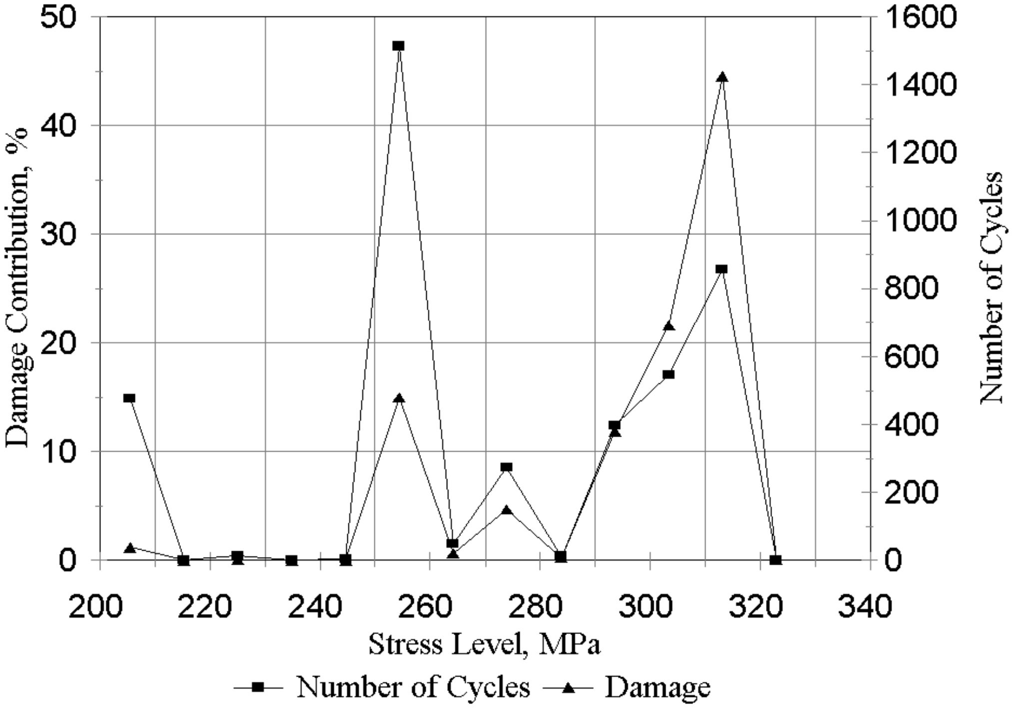


Figure 91. Stress Level Damage Contributions, Mod 1 Spectrum, R = 0.5, 414 MPa Maximum Stress.

Unmodified WISPERX Spectrum Fatigue Life Predictions

Fatigue lifetime predictions for a spectrum that contains a wide variety of R-values such that cycles of loading may be tensile, compressive or reversing require a consideration of the mode of failure. All previous discussions were restricted to tests and calculations that avoided this problem by forcing a consistent, known failure mode.

Consider that the failure mode must change from one that is tension dominated to one that is compression dominated as the R-value changes from 0.1 to 10 [9]. Depending upon the laminate, the transition could occur between R-values of 0 and ∞, as is shown in Figure 94 (Figure 94 is a modification of Figure 5 to better illustrate the transition region). The fact of this transition is evident in analysis of the stress (y-axis) intercept for the S-N curves for the constant amplitude fatigue tests, such as Figures 33 through 37.

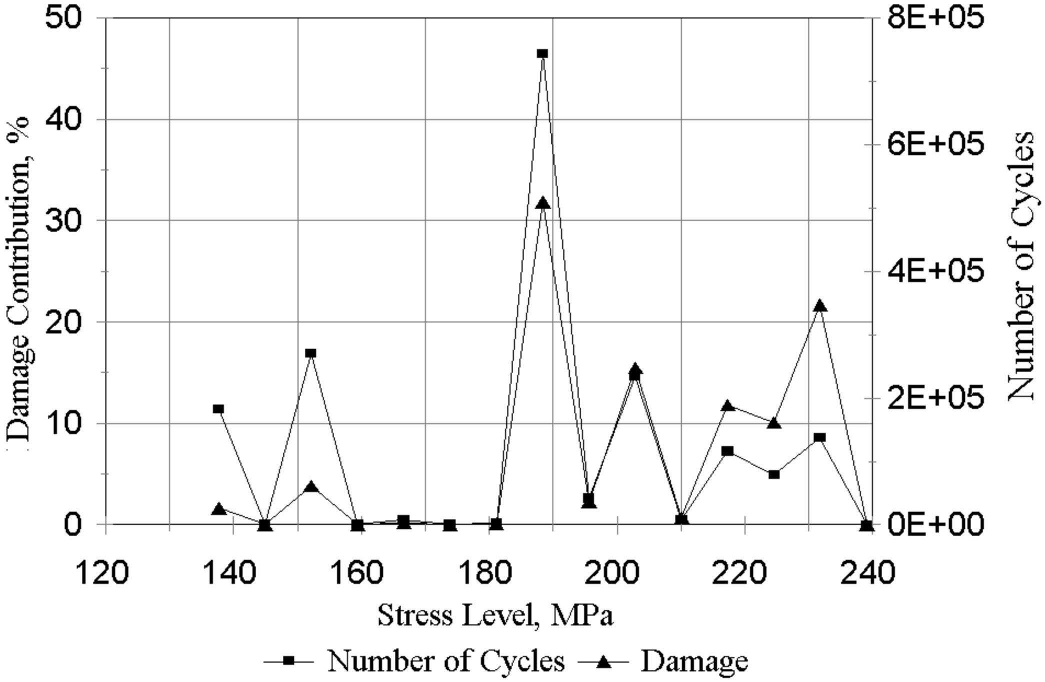


Figure 92. Stress Level Damage Contributions, Mod 1 Spectrum, R = 0.5, 241 MPa Maximum Stress.

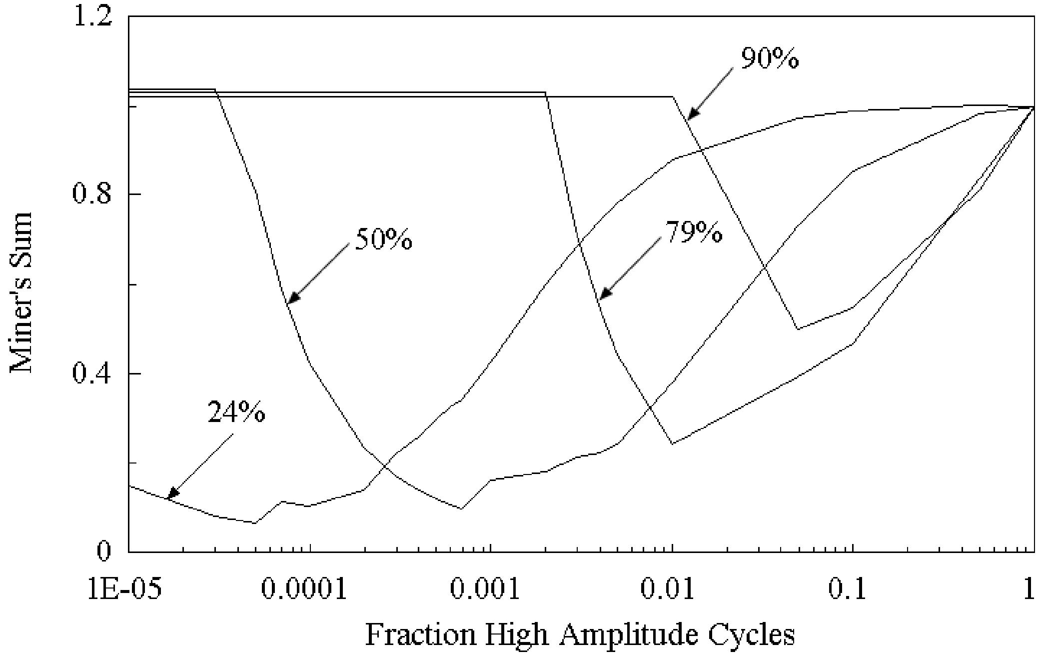


Figure 93. Two-level block loading Load Level Sensitivity, Low-Block Amplitude as Percent of High-Block Amplitude (nonlinear residual strength model prediction with ν = 0.265, exponential fatigue model).

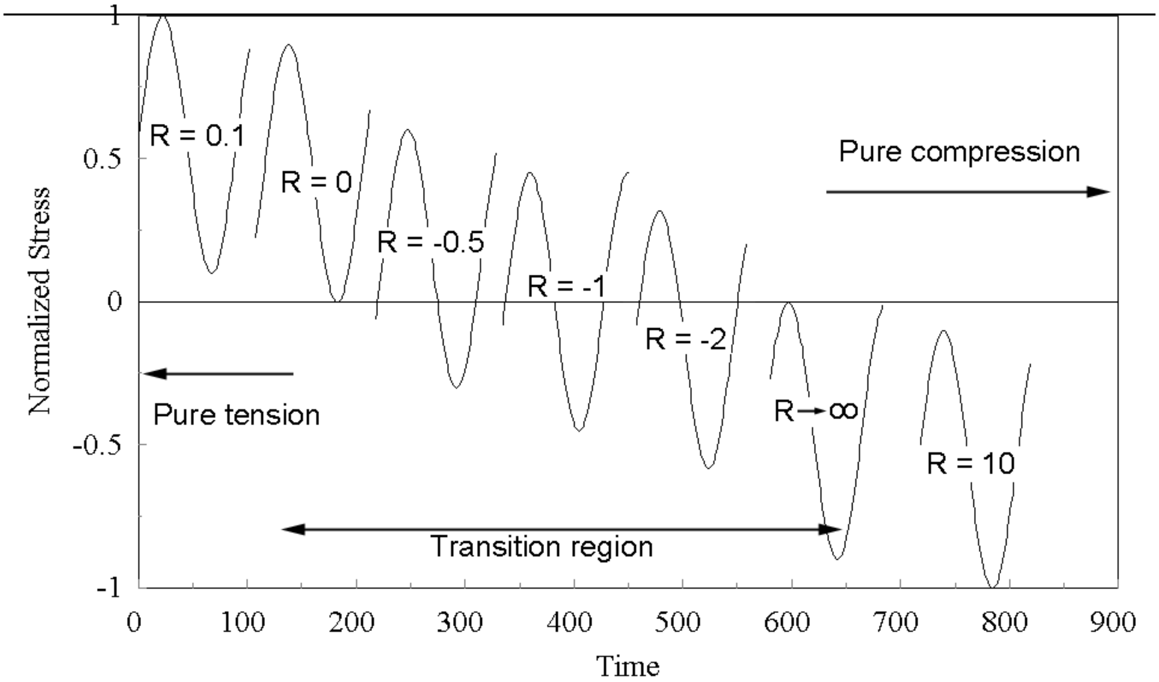


Figure 94. Transition From Tensile to Compressive Failure Mode, Constant Amplitude.

In order to apply the residual strength lifetime prediction models for this type of variable amplitude spectrum, the demarcation R-value must be known, as there are two distinct residual strength curves for compression and tension loading. This is not the case for application of Miner's rule in that the accepted interpolations from a Goodman diagram circumvent this need.

Lacking test information to allow determining this demarcation R-value, some logically developed value must be used. Hypothesize that the damage a laminate may suffer is dependent upon the ratio of the maximum stress to the ultimate strength for either tension or compression loading. If this were the case consider that the R-value that allows equal ratios of the tension maximum stress to the ultimate tensile stress and the compression minimum stress to the ultimate compressive stress would be the transition R-value. For equivalent damage from either the maximum tensile or compressive load then based upon the above hypothesis,

$$\frac{\sigma_{\min}}{\sigma_{ucs}} = \frac{\sigma_{\max}}{\sigma_{uts}} \tag{17}$$

Upon considering the same stress range (alternating stress), as shown in Figure 94, Equation 17 reduces to:

$$R = \frac{\sigma_{ucs}}{\sigma_{uts}} \tag{18}$$

This R-value, for the tested laminate, was -0.63. This was then used as the demarcation R-value for the selection of the residual strength curve to be applied for any given cycle in a variable amplitude spectrum containing tensile, compressive and reversing loading cycles.

The lifetime predictions based upon this method of failure mode demarcation are shown in Figures 95 and 96 for the exponential and power law fatigue models, respectively. Only the two lifetime prediction rules of NRSD and Miner's rule were employed as the LRSD and Miner's rule have yielded very similar results. The incremental value for the stress level was held coarse and hence any spectrum effects at the low cycles are not as evident as in previous Figures 83 through 88. The nonlinear residual strength rule was more conservative than the Miner's rule. The prediction rules based upon the exponential fatigue model do not seem to follow the general slope of the experimental data. The predictions based upon the exponential fatigue model over-predict life at the low cycles and under-predict life at the high cycles. The rule predictions based upon the power law fatigue model over-predict life throughout the life, yet seem to follow the general slope much better.

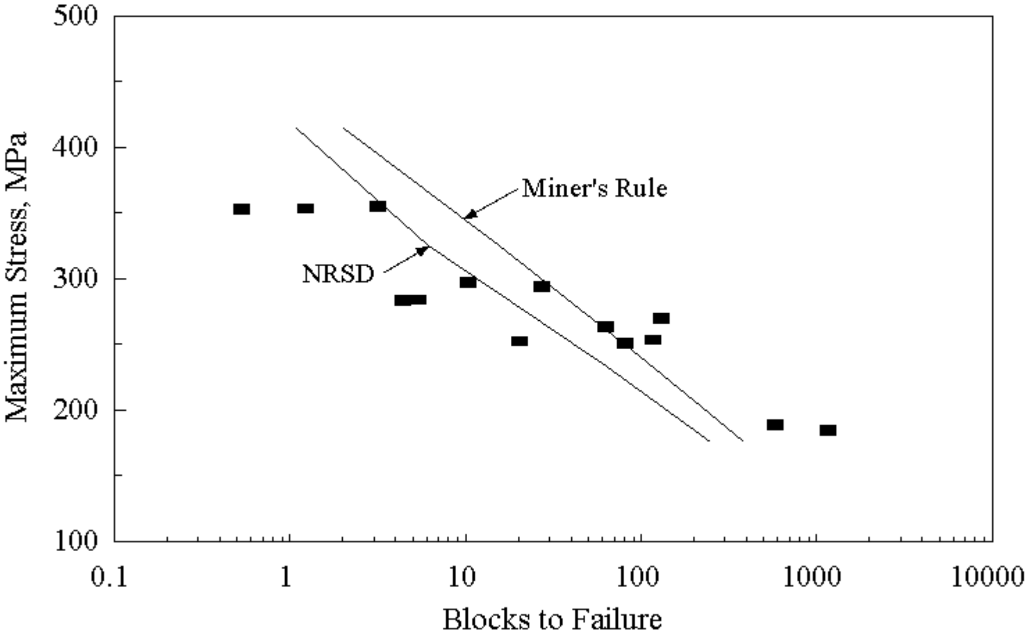


Figure 95. Unmodified WISPERX Spectrum Lifetime Predictions, Exponential Fatigue Model Including All Data.

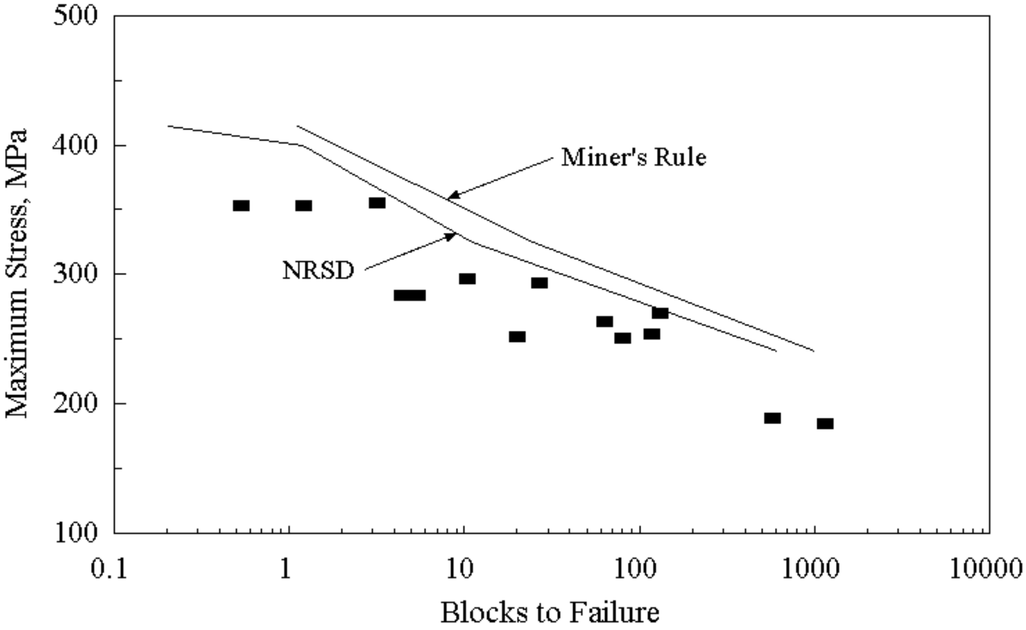


Figure 96. Unmodified WISPERX Spectrum Lifetime Predictions, Power Law Fatigue Model Including All Data.

Comparisons between the WISPERX results of van Delft [5] and the present fatigue results for the WISPERX spectrum are shown in Figure 97. The lifetimes predicted by van Delft are much greater than those of the present research, similar to the results presented by Sutherland and Mandell [10]. Prediction rules employed by van Delft and during this present research over-predict the actual lifetimes.

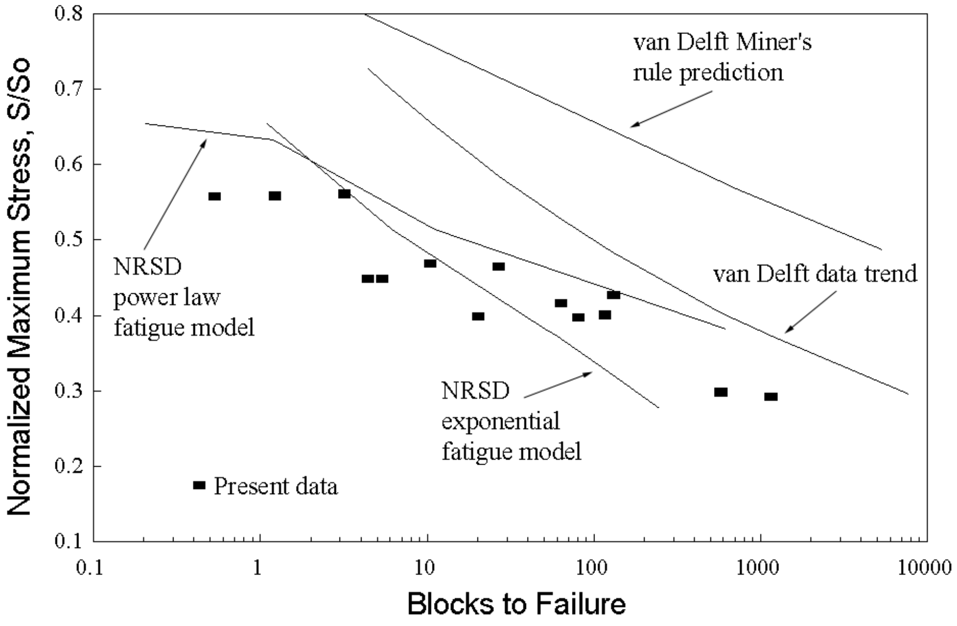


Figure 97. Comparison of WISPERX Lifetime Predictions.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The research conducted and reported here involved the development of an experimental program that, when implemented, generated a substantial quantity of fatigue data. Test methodologies, including material selection, test specimen geometry, data acquisition, and testing machine performance, were all held to unusually high standards, so that meaningful conclusions could be rendered relative to the accuracy of theoretical predictions in this and future studies. The data are those of the fatigue of specimens of the selected laminate, subjected to a variety of loads spectra and cycled until the specimens were sufficiently failed that they could not support loads. Other researchers have primarily investigated the response of laminates to either constant amplitude or simple two-level block loading spectra. The present work extends the complexity to multi-level block and variable amplitude spectra.

Three fatigue life prediction models were employed to estimate the life of laminates subjected to a variety of loading spectra. Comparisons are made between the prediction models and the experimental data. While additional work with other models and loads spectra may be necessary to definitively prove the superiority of one prediction scheme over others, these results do allow limited conclusions to be drawn as to: (1.) the preferred methods of extrapolating the baseline constant amplitude S-N trends to higher cycles and (2.) the accuracy of cumulative damage models for particular spectrum characteristics.

Lifetime Observations and Application to Blade Design

Spectra involving two or more different stress levels generally resulted in lifetimes less than predicted by Miner's rule. This was not entirely expected. Other researchers [42] have reported that, for the application of two stress levels, with the second level run to specimen failure, the actual lifetimes may be greater or lesser than predicted by Miner's rule. The conclusion that Miner's rule is non-conservative for nearly all spectra tested raised questions as to the current status of wind turbine blades designed using this method. Fortunately, blades appear to be generally over-designed in terms of strength and fatigue lifetime, with designs often driven by stiffness related factors.

Better agreement between predictions and data was found by the application of residual strength based rules than by the use of the linear Miner's rule. This was particularly notable where the spectra (repeated block spectra) had sufficient variations in stress levels to separate the prediction rules. Although the nonlinear residual strength degradation rule introduces an unknown parameter that must be determined experimentally, it does provide a better prediction of lifetimes than the linear residual strength rule. The exponential parameter in Equation 16 has not been optimized; in fact the parameter may be a function of several factors, such as stress level, fatigue age and laminate selection. Presently the parameter has been given a value of 0.265, the result of a rudimentary error analysis of residual strength data and a mere visual fitting of the prediction results to experimental data. The choice of a nonlinear exponential parameter less than 1.0 indicates a relatively rapid decrease in residual strength early in the specimen or blade lifetime. This choice is supported by all of the different types of spectra as well as direct residual strength measurements. Thus, not only is it practical to predict changes in material and blade strength at different fractions of test or service lifetime, it may be essential in designing against the occurrence of “hurricane” extreme load conditions.

Comments on Spectrum Effects

The Mod 1, Mod 2 and WISPERX spectra are rather benign and as such fatigue results for these spectra, do not differ greatly from the similar constant amplitude fatigue results. Regression results of the Mod 1 spectrum test results at an R-value of 0.1 produced a log-log inverse slope, regression parameter m, of 12.0, whereas, the constant amplitude equivalent was 11.5. Similarly for the Mod 1 spectrum at an R-value of 0.5, the inverse slope was 14.5 compared to the constant amplitude value of 14.4. The Mod 2 spectrum, which included the one large cycle, and was forced to an R-value of 0.1, produced an inverse slope of 13.9; compare this to the constant amplitude value of 11.5. It appears that for the case of the random spectrum of limited stress variation, such as the Mod 1 spectrum, the fatigue sensitivity of the laminate is little different from that achieved by a constant amplitude spectrum. The single large cycle of the Mod 2 spectrum does cause some effect; the fatigue sensitivity of this spectrum deviates from the constant amplitude equivalent.

The WISPERX spectrum has an average R-value of approximately 0.4. The fatigue inverse slope for these tests was 14.2, not much removed from the 14.4 of the constant amplitude (R-value = 0.5) fatigue results.

Spectra such as the two-level block loading spectra reported, have a greater variation in the cyclic load levels and have a greater effect on the fatigue lifetime predictions. This is born out by the difference seen in the lifetime predictions of the two-level block loading as shown in Figures 77 through 80. The differences among the Miner’s rule, linear residual strength degradation rule and the nonlinear residual strength rule are more pronounced than those seen in the WISPERX spectra results. One may presume, and wish to investigate, that the greater variation in stress levels that a spectrum contains, the more important the selection of the fatigue lifetime prediction rule.

Stress Level Sequencing Effects

An investigation into the possibility of any stress level sequencing effects on lifetimes has not shown this to be a significant factor, at least for the sequences selected. The spectra of different sequences of cycles in repeated blocks did not have an effect on the life of the specimens. Yet, when the blocks are not repeated (the second block continued until failure), the sequencing does produce significantly different results. Upon comparing the results of the residual strength degradation lifetime predictions to the experimental results of other investigators [43], the fact that sequencing is important for this special case was confirmed both experimentally and theoretically. Consequently, it is believed that sequencing effects of the cycles experienced during the actual service of components subjected to realistic random spectra, is not significant. This observation allows for the possibility that relatively simple cumulative damage rules may be used (although load conditions where compressive and tensile failure modes interact significantly may prove to cause complications).

Fatigue Model Selection

The results of the constant amplitude fatigue testing were summarized into two fatigue models based upon exponential and power law regression curves representing the data. Generally, for the two-level block loading fatigue testing, the selection of the fatigue model is immaterial. Application of either the exponential or the power law fatigue models caused little difference in the lifetime predictions for the two-level block loading loading spectra. This appears to be due to a limit of the number of cycles that are placed within each of the two blocks. These tests were typically extending over a range of a few thousand to a million cycles, a range over which the two fatigue models differ only slightly, and extrapolation to lower stresses using the models is unnecessary. Testing at lower stress levels for each block would force the testing into greater numbers of cycles, at which point, the selection of the fatigue model may become significant if the constant amplitude input trends require extrapolation beyond the range of experimental data.

The significance of the higher number of cycles was evident in the modified and unmodified WISPERX fatigue testing. In fact, the power law fatigue model provided a better lifetime prediction than the exponential model when the number of cycles was extended by an order of magnitude to 10 million. In fact, none of the models predicted the unmodified WISPERX data with adequate accuracy for design, and most predictions were non-conservative. A more conservative, practical approach at this time would be to use a power law fatigue model with a Miner's Sum of 0.1 instead of 1.0, as suggested by Echtermeyer, et. al. [50].

Recommendations for Future Work

Many questions are still unanswered in regards to laminate response to spectrum loading; in fact work is still in progress in this research area. Items of ongoing work and areas of potential work are discussed below.

Spectrum Considerations

Upon studying the relatively benign WISPERX spectrum as compared to some of the two-level block loading spectra, and the various rule prediction accuracies for those spectra, testing of other more robust spectra may provide more insight into rule selection. Other random spectra have been collected; wind turbine start/stop sequences, WISPER, FALSTAFF, as well as spectrum based upon data collected from operational wind turbines in Montana. Lifetimes of the laminate when subjected to these varied spectra may provide more insight into fatigue prediction, since loads often are more variable than WISPERX.

Compressive Residual Strength

There appears to be some differences in the response of the laminate to tensile and compressive loading as evidenced in the two-level block loading testing. Residual strength testing of laminates was performed only for the tensile loading case. Results indicated the residual strength degradation lifetime prediction rule warrants use. Testing of the residual strength of the laminate subjected to compressive loading would be of interest.

Failure Mode Transition

At some loading condition, the failure mode transitions from tensile to compressive. The application of the residual strength degradation lifetime prediction model is somewhat dependent upon this transition point for the selection of the proper strength degradation path. This warrants an investigation into the failure mode and the breakpoint between these two fundamental loading conditions. Testing at a finer grid of R-values in the region surrounding $R = -1$ would be of interest.

Residual Strength Model Refinement

The nonlinear residual strength model was somewhat calibrated to the experimental data by selection of the exponent, ν, in Equation 14. Adjustment of this single parameter causes a shifting of the predictions, in a manner similar to offset adjustment in instrumentation calibration. The introduction of a second variable of, as yet an unknown function, may allow better calibration of the model to fit the experimental data.

Simple magnitude shifting of the exponent can provide a better correlation with the experimental data for the unmodified WISPERX case that used the power law fatigue model. Unfortunately, this would not correct the lack of fit as observed in some of the two-level block loading fatigue cases wherein the model is under-conservative for a spectrum of large high-amplitude cycle fractions and over-conservative for a spectrum with a smaller fraction. The second parameter may achieve a better calibration.

High Cycle Spectrum Fatigue Testing

Since the desired life of wind turbine blades can exceed 30 years or over 10^9 cycles, investigation of lifetimes of this magnitude, for laminates subjected to spectrum loading needs to be performed. It appears upon observation of the data in Figures 77 through 80, 83 through 88 and 95 and 96, the power law fatigue model provides a better correlation to the data than does the exponential fatigue model. Additional testing in the higher cycle region may provide more confidence for this conclusion.

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APPENDICES

APPENDIX A

SPECTRUM FATIGUE DATABASE

Description of Table Headings for Appendix A

1) Test and coupon number - The unique identifying number for each test listed in the DOE/MSU Database, and test coupon identifier, respectively. Coupons were manufactured sequentially from plates and randomly selected from the stock and sequentially numbered. The tests were not conducted in this sequential number, but randomly in batches.

2) Comment - The comments for each test provide some insight as to the type of test and loading.

   An entry such as that of test number 7934, involving coupon number 191, “2 block, 10H/50000L" indicates that this test was conducted with a two-level block loading spectrum with the first block’s maximum stress cycled 10 times and the second block cycled 50000 times. The sequence was repeated until coupon failure. The High (H) and Low (L) stress is listed in the Maximum Stress column.

   1 cycle indicates that this particular test was an ultimate strength test.

   Constant Amplitude indicated that the test was conducted in a sinusoidal waveform with a fixed R-value.

   Entries such as “Wisperx”, “WisxR05", “WisxR01", “Wisxmix”, or “Wispk” indicate that a modified WISPERX or original WISPERX spectrum was used to load the specimen.

3) Maximum Stress - This was the maximum positive stress of the tension-tension or reversed (tension-compression) waveform. For compressive tests (compression-compression), the highest compressive stress is listed. For multi-level loadings, the stresses are listed in the order from highest to lowest, which correspond to the H, M, L levels listed in the comment column..

4) R-Value - this was the ratio of the minimum maximum stress to the maximum applied stress.

5) Freq, Hz - The frequency of the test. Ultimate strength tests were conducted at the same displacement rate as the cyclic tests, 13 mm/second. These single cycle tests are indicated by the entry “*”.

6) # High Cycles - This column lists the number of cycles conducted at the high amplitude (H) stress level.

7) # Low Cycles - The number of cycles conducted at the low amplitude (L) stress level. Tests of more than two-level block loading are summarized in Tables 7, 8 and 9 of the

text.

8) Total Cycles - The total number of cycles (# High + # Low) of the test.

9) Program - This column lists the computer program which was run during the test, detailed below.

For fatigue cycling, the applied loads are described below as the peak and valley of the waveform. The data input files utilize a percentage of maximum applied load with 1.0 = maximum load, 0.1 = 10 percent of the maximum load. Positive is tensile, negative is compressive. Other general programs used were: WR = Instron Waverunner software, and CA= constant amplitude (R-value) test. An * signifies static (one - cycle) tests, which were performed at a displacement ramp rate of 13 mm/s.

As an example, program COMP3 is described as: COMP3- [1.0, 0.1] X10 + [0.75, 0.075] X 10 if the desired maximum fatigue stress is 500 MPa, the load sequence (peak, valley) for one pass of the data file would be: [500, 50, 500, 50, 500, 50, 500, 50, 500, 50, 500, 50, 500, 50, 500, 50, 500, 50, 500, 50, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5, 375, 37.5]. This file would then repeat from the start and continue to repeat until coupon failure. All the program types for tests 7510 through 8499 are described below.

REPEATED BLOCKS OF TWO LEVEL LOAD AMPLITUDES
COMP1- [1.0, 0.1] X10 + [0.75, 0.075] X 1000
COMP2- [1.0, 0.1] X10 + [0.75, 0.075] X 100
COMP3- [1.0, 0.1] X10 + [0.75, 0.075] X 10
COMP4- [1.0, 0.1] X10 + [0.75, 0.075] X 10000
LOAD1- [1.0, 0.1] X10 + [0.7917, 0.0792] X1000
LOAD2- [1.0, 0.1] X10 + [0.5833, 0.0583] X1000
LOAD3- [1.0, 0.1] X10 + [0.50, 0.05] X1000
LOAD4- [1.0, 0.1] X10 + [0.7368, 0.0737] X1000
LOAD5- [1.0, 0.1] X10 + [0.6316, 0.0632] X1000
LOAD6- [1.0, 0.1] X10 + [0.8571, 0.0858] X1000
LOAD7- [1.0, 0.5] X10 + [0.7917, 0.0792] X1000
LOAD8- [1.0, 0.5] X10 + [0.5833, 0.2917] X1000
LOAD9- [1.0, 0.5] X10 + [0.7368, 0.3684] X1000
LOAD10- [1.0, 0.1] X1000
LOAD11- [1.0, 0.5] X1000
LOAD12- [1.0, 0.5] X10 + [0.5833, 0.2917] X100
LOAD13- [1.0, 0.5] X10 + [0.5833, 0.2917] X1000
LOAD14- [1.0, 0.5] X10 + [0.7368, 0.3684] X1000
LOAD15- [1.0, 0.5] X10 + [0.7368, 0.3686] X100
LOAD16- [1.0, 0.5] X10 + [0.5833, 0.2917] X10000
LOAD17- [1.0, 0.5] X10 + [0.7368, 0.3684] X10000
LOAD18- [1.0, 0.1] X10 + [0.5833, 0.0583] X1000
RAND1- [0.7917, 0.0792] with [1, 0.1] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992

cycles), 1010 total cycles per pass.
RAND2- [0.5833, 0.0583] with [1, 0.1] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND3- [0.50, 0.05] with [1, 0.1] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND4- [0.7368, 0.037] with [1, 0.1] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND5- [0.6315, 0.0632] with [1, 0.1] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND6- [0.8571, 0.0857] with [1, 0.1] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND7- [0.7917, 0.0792] with [1, 0.5] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND8- [0.5833, 0.2917] with [1, 0.5] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RAND9- [0.7368, 0.3684] with [1, 0.5] at (25, 88, 129, 136, 212, 346, 582, 860, 922 and 992 cycles), 1010 total cycles per pass.
RANDOM1- [0.632, 0.0632] with [1, 0.1] at (24, 61, 166, 263, 358, 637, 826, 834, 905 and 909 cycles), 996 total cycles per pass.
RANDOM2- [0.632, 0.0632] with [1, 0.1] at (24, 61, 166, 263, 358, 637, 826, 834, 905 and 909 cycles), 1011 total cycles per pass.
RANDOM3- [1, 0.1] X10 + [0.632, 0.0632] X1000
REVERS- [1.0, -1.0] X1000
R10IN100- [1.0, 0.1] X10 + [0.6316, 0.0632] X1000
R10LD1- [1.0, 0.1] X10 + [0.6316, 0.0632] X100
R10LD2- [1.0, 0.1] X10 + [0.6316, 0.0632] X10
R1IN100- [1.0, 0.1] X1 + [0.6316, 0.0632] X100
RVR1- [1.0, -1.0] X10 + [0.6, -0.6] X 10
RVR2- [1.0, -1.0] X10 + [0.6, -0.6] X 100
RVR3- [1.0, -1.0] X10 + [0.6, -0.6] X 1000
RVR4- [1.0, -1.0] X10 + [0.6, -0.6] X 10000

MODIFIED AND UNMODIFIED WISPERX SPECTRA.

Copies of WISPER and WISPERX data files were obtained over the Internet from NLR in the Netherlands. at http://www.nlr.nl/public/. Copies of the NLR papers on WISPER and WISPERX can also be downloaded from this site. WISPERX is included in its entirety in NLR TP 91476. Page 27 of NLR TP 91476 gives addresses and phone numbers for requesting copies of WISPER and WISPERX on magnetic media.

UNMODIFIED WISPERX

The WISPERX file contains a data stream of peaks and valleys for a loading sequence between values of 1 to 64. Compression was defined as values 1 to 25 and tensile as 25 to 64, with a zero stress value defined as 25. The WISPERX file was recalculated to values between 0.0 and 1.0 by the expression y = (x-25)/(64-25), where each file entry was input as the variable x. The very first entry in the unmodified WISPERX file was 25; consequently, the first entry in the recalculated wisperx file was 0.0. That is, the first entry is a no-load condition. This new file would have a maximum entry of 1.0 and a minimum entry of -0.6154.

The other four spectra were then created (modified) from this recalculated data file (wisperx).

Wispk (MOD2):

Consider the waveform to be a sequence of peaks and valleys. The first entry is zero, symbolizing a no-load starting point. Each following even numbered entry, (eg. 2nd, 4th, 6th values in the stream) would be peaks while the odd entries (3rd, 5th, 7th values) would be valleys. The peak and its following valley (eg, the 2nd and 3rd values in the stream) values were considered to define the max and min of a cycle. Wispk was constructed by reading each peak value from the recalculated WISPERX file and calculating a new valley value by multiplying the cycle's peak value by 0.1. This then gives the constant R-value of 0.1. The peak value and the new valley value were saved to a new file, Wispk. The old valley values were never used.

Wismix (MOD3):

This was an attempt to provide a mix of only 0.1 and 0.5 R-values. This was created similar to that for the Wispk waveform. Each peak and valley value were read and used to calculate an R-value of the original WISPERX file (would be the same in the recalculated WISPERX file, wisperx). A comparison was made of the original R-value to R-values of 0.1 and 0.5. If the original were closer to 0.1 than to 0.5 the cycle was forced to an R-value of 0.1 by replacing the valley value by 0.1multiplied by the peak value. Conversely, if the original R-value were closer to 0.5 than to 0.1, the cycle was forced to an R-value of 0.5 by replacing the valley value by 0.5 multiplied by the peak value.

MOD1 SPECTRA (WisxR01 and WisxR05)

WisxR01 (MOD1, R=0.1):

This waveform was created by reading the maximum and minimum for each cycle. The cycle was retained if it was tension-tension. Each remaining valley value was replaced with 0.1multiplied by the peak value. This waveform would be similar to Wispk, with the exception of the removal of the handful of cycles that were reversing cycles. Unfortunately, the single large event (largest peak value) is followed by a compressive minimum load. The method used to create this file then removed the largest event. This waveform is of constant R-value, 0.1.

WisxR05 (MOD1, R=0.5):

Nearly the same process, as described in WisxR01, was used to create this waveform. The only exception is that the retained cycle's valley values were replaced with 0.5 multiplied by the peak value. This waveform is of constant R-value, 0.5.

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
MATERIAL DD5P									
7510	6	1 cycle	766	*	13	----	----	1	WR
7511	7	1 cycle	813	*	13	----	----	1	WR
7512	8	1 cycle	824	*	13	----	----	1	WR
7513	85	1 cycle	716	*	13	----	----	1	WR
7514	105	1 cycle	741	*	13	----	----	1	WR
7515	2	constant amplitude	414	0.1	10	----	----	4717	WR
7516	3	constant amplitude	414	0.1	10	----	----	2711	WR
7517	4	constant amplitude	414	0.1	10	----	----	1812	WR
7518	9	constant amplitude	414	0.1	10	----	----	3711	WR
7519	32	constant amplitude	414	0.1	10	----	----	4221	WR
7520	70	constant amplitude	414	0.1	10	----	----	1743	WR
7521	71	constant amplitude	414	0.1	10	----	----	1767	WR
7522	72	constant amplitude	414	0.1	10	----	----	1017	WR
7523	75	constant amplitude	414	0.1	10	----	----	1515	WR
7524	84	constant amplitude	414	0.1	10	----	----	1697	WR
7525	103	constant amplitude	414	0.1	10	----	----	1496	WR
7526	106	constant amplitude	414	0.1	10	----	----	5660	WR
7527	97	2 block, 10H/10L	414 / 241	0.1	10	4024	4020	8044	WR
7528	99	2 block, 10H/10L	414 / 241	0.1	10	5956	5950	11906	WR
7529	48	2 block, 10H/56L	414 / 241	0.1	10	8610	44720	53330	WR
7530	38	2 block, 10H/56L	414 / 241	0.1	10	10100	52468	62568	WR
7531	73	2 block, 10H/56L	414 / 241	0.1	10	1130	5824	6954	WR
7532	74	2 block, 10H/56L	414 / 241	0.1	10	1980	10244	12224	WR
7533	76	2 block, 10H/56L	414 / 241	0.1	10	1190	6188	7378	WR
7534	40	2 block, 10H/112L	414 / 241	0.1	10	5040	56336	61376	WR
7535	44	2 block, 10H/112L	414 / 241	0.1	10	6440	72016	78456	WR
7536	90	2 block, 10H/112L	414 / 241	0.1	10	720	7952	8672	WR
7537	101	2 block, 10H/112L	414 / 241	0.1	10	5337	59696	65033	WR
7538	104	2 block, 10H/112L	414 / 241	0.1	10	2380	26544	28924	WR
7539	77	2 block, 10H/112L	414 / 241	0.1	10	1080	11984	13064	WR
7540	20	2 block, 5H/56L	414 / 241	0.1	10	7950	88928	96878	WR
7541	28	2 block, 10H/112L	414 / 241	0.1	10	7855	87808	95663	WR
7542	25	2 block, 5H/165L	414 / 241	0.1	10	6880	226061	232941	WR
7543	26	2 block, 5H/165L	414 / 241	0.1	10	6415	211530	217945	WR
7544	39	2 block, 10H/334L	414 / 241	0.1	10	4340	144622	148962	WR
7545	46	2 block, 10H/334L	414 / 241	0.1	10	3920	130594	134514	WR
7546	78	2 block, 10H/334L	414 / 241	0.1	10	1150	38076	39226	WR
7547	94	2 block, 10H/334L	414 / 241	0.1	10	782	26052	26834	WR
7548	23	2 block, 5H/1500L	414 / 241	0.1	10	2025	607500	609525	WR
7549	24	2 block, 5H/1500L	414 / 241	0.1	10	3090	925500	928590	WR
7550	27	2 block, 5H/500L	414 / 241	0.1	10	2850	285000	287850	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7551	36	2 block, 5H/500L	414 / 241	0.1	10	3270	327000	330270	WR
7552	37	2 block, 10H/667L	414 / 241	0.1	10	2860	189428	192288	WR
7553	41	2 block, 10H/667L	414 / 241	0.1	10	1727	114057	115784	WR
7554	82	2 block, 10H/667L	414 / 241	0.1	10	520	34017	34537	WR
7555	95	2 block, 10H/667L	414 / 241	0.1	10	903	60030	60933	WR
7556	42	2 block, 10H/1000L	414 / 241	0.1	10	3670	366000	369670	WR
7557	45	2 block, 10H/1000L	414 / 241	0.1	10	2780	277000	279780	WR
7558	79	2 block, 10H/1000L	414 / 241	0.1	10	470	46000	46470	WR
7559	89	2 block, 10H/1000L	414 / 241	0.1	10	293	28527	28820	WR
7560	100	2 block, 10H/1000L	414 / 241	0.1	10	2416	241000	243416	WR
7561	43	2 block, 10H/3000L	414 / 241	0.1	10	1960	588000	589960	WR
7562	47	2 block, 10H/3000L	414 / 241	0.1	10	1330	399000	400330	WR
7563	92	2 block, 10H/3000L	414 / 241	0.1	10	1102	330000	331102	WR
7564	96	2 block, 10H/3000L	414 / 241	0.1	10	710	213000	213710	WR
7565	22	2 block, 5H/4500L	414 / 241	0.1	10	1600	1435500	1437100	WR
7566	29	2 block, 5H/45000L	414 / 241	0.1	10	400	1800000	1800400	WR
7567	19	2 block, 10H/9000L	414 / 241	0.1	10	670	594000	594670	WR
7568	81	2 block, 10H/9000L	414 / 241	0.1	10	30	25918	25948	WR
7569	91	2 block, 10H/9000L	414 / 241	0.1	10	50	45000	45050	WR
7570	102	2 block, 10H/9000L	414 / 241	0.1	10	795	711000	711795	WR
7571	107	2 block, 10H/9000L	414 / 241	0.1	10	680	609298	609978	WR
7572	31	constant amplitude	241	0.1	10		4501339	4501339	WR
7573	83	constant amplitude	241	0.1	10		628444	628444	WR
7574	93	constant amplitude	241	0.1	10		1407916	1407916	WR
7575	98	constant amplitude	241	0.1	10		3403091	3403091	WR
7576	17	constant amplitude	241	0.1	10		3096821	3096821	WR
7577	18	constant amplitude	241	0.1	30		1709382	1709382	WR
7578	11	constant amplitude	500	0.1	10	877		877	WR
7579	13	constant amplitude	500	0.1	10	584		584	WR
7580	14	constant amplitude	690	0.1	10	28		28	WR
7581	33	constant amplitude	690	0.1	10	67		67	WR
7582	34	constant amplitude	500	0.1	10	1113		1113	WR
7583	35	constant amplitude	690	0.1	10	39		39	WR
7584	86	constant amplitude	500	0.1	10	463		463	WR
7585	87	constant amplitude	500	0.1	10	527		527	WR
MATERIAL DD11									
7586	114	1 cycle	508	*	13	1		1	WR
7587	115	1 cycle	577	*	13	1		1	WR
7588	108	constant amplitude	414	0.1	10	97		97	WR
7589	111	constant amplitude	414	0.1	10	226		226	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7590	123	constant amplitude	414	0.1	10	801		801	WR
7591	124	constant amplitude	414	0.1	10	392		392	WR
7592	119	constant amplitude	414	0.1	10	29		29	WR
7593	109	constant amplitude	241	0.1	10		217518	217518	WR
7594	110	constant amplitude	241	0.1	10		208911	208911	WR
7595	127	constant amplitude	241	0.1	10		107287	107287	WR
7596	116	constant amplitude	472	0.1	10	37		37	WR
7597	117	constant amplitude	341	0.1	10	2729		2729	WR
7598	118	constant amplitude	462	0.1	10	78		78	WR
7599	122	2 block, 10H/10L	414 / 241	0.1	10	368	360	728	WR
7600	120	2 block, 10H/112L	414 / 241	0.1	10	576	6384	6960	WR
7601	126	2 block, 10H/112L	414 / 241	0.1	10	237	2576	2813	WR
7602	112	2 block, 10H/334L	414 / 241	0.1	10	21	668	689	WR
7603	121	2 block, 10H/1000L	414 / 241	0.1	10	88	8000	8088	WR
7604	125	2 block, 10H/112L	386 / 225	0.1	10	1228	13664	14892	WR
7605	113	2 block, 10H/3000L	414 / 241	0.1	10	104	30000	30104	WR
MATERIAL DD16									
7606	128	1 cycle	493	*	13	----	----	1	WR
7607	141	1 cycle	524	*	13	----	----	1	WR
7608	173	1 cycle	493	*	13	----	----	1	WR
7609	268	1 cycle	473	*	13	----	----	1	WR
7610	269	1 cycle	468	*	13	----	----	1	WR
7611	270	1 cycle	465	*	13	----	----	1	WR
7612	271	1 cycle	489	*	13	----	----	1	WR
7613	272	1 cycle	473	*	13	----	----	1	WR
7614	273	1 cycle	646	*	13	----	----	1	WR
7615	274	1 cycle	680	*	13	----	----	1	WR
7616	296	1 cycle	489	*	13	----	----	1	WR
7617	306	1 cycle	673	*	13	----	----	1	WR
7618	329	1 cycle	542	*	13	----	----	1	WR
7619	349	1 cycle	558	*	13	----	----	1	WR
7620	283	1 cycle	649	*	13	----	----	1	WR
7621	383	1 cycle	652	*	13	----	----	1	WR
7622	410	1 cycle	638	*	13	----	----	1	WR
7623	430	1 cycle	598	*	13	----	----	1	WR
7624	479	1 cycle	657	*	13	----	----	1	WR
7625	474	1 cycle	629	*	13	----	----	1	WR
7626	635	1 cycle	670	*	13	----	----	1	WR
7627	652	1 cycle	619	*	13	----	----	1	WR
7628	653	1 cycle	676	*	13	----	----	1	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7629	655	1 cycle	688	*	13	----	----	1	WR
7630	666	1 cycle	670	*	13	----	----	1	WR
7631	671	1 cycle	687	*	13	----	----	1	WR
7632	726a	1 cycle	647	*	13	----	----	1	WR
7633	739	1 cycle	644	*	13	----	----	1	WR
7634	756	1 cycle	664	*	13	----	----	1	WR
7635	765	1 cycle	621	*	13	----	----	1	WR
7636	774	1 cycle	686	*	13	----	----	1	WR
7637	783	1 cycle	696	*	13	----	----	1	WR
7638	812	1 cycle	-399	*	13	----	----	1	WR
7639	818	1 cycle	-396	*	13	----	----	1	WR
7640	824	1 cycle	-405	*	13	----	----	1	WR
7641	830	1 cycle	-368	*	13	----	----	1	WR
7642	831	1 cycle	-410	*	13	----	----	1	WR
7643	832	1 cycle	-368	*	13	----	----	1	WR
7644	833	1 cycle	-416	*	13	----	----	1	WR
7645	834	1 cycle	-379	*	13	----	----	1	WR
7646	835	1 cycle	-435	*	13	----	----	1	WR
7647	865	1 cycle	-427	*	13	----	----	1	WR
7648	866	1 cycle	-408	*	13	----	----	1	WR
7649	867	1 cycle	-406	*	13	----	----	1	WR
7650	868	1 cycle	-387	*	13	----	----	1	WR
7651	869	1 cycle	-419	*	13	----	----	1	WR
7652	880	1 cycle	-371	*	13	----	----	1	WR
7653	881	1 cycle	-404	*	13	----	----	1	WR
7654	882	1 cycle	-427	*	13	----	----	1	WR
7655	883	1 cycle	-397	*	13	----	----	1	WR
7656	884	1 cycle	-421	*	13	----	----	1	WR
7657	885	1 cycle	-394	*	13	----	----	1	WR
7658	886	1 cycle	-411	*	13	----	----	1	WR
7659	887	1 cycle	-374	*	13	----	----	1	WR
7660	888	1 cycle	-415	*	13	----	----	1	WR
7661	889	1 cycle	-413	*	13	----	----	1	WR
7662	646	1 cycle	569	*	13	----	----	1	WR
7663	139	constant amplitude	330	0.1	10	----	----	2297	WR
7664	140	constant amplitude	323	0.1	10	----	----	1914	WR
7665	151	constant amplitude	205	0.1	10	----	----	274271	WR
7666	152	constant amplitude	202	0.1	10	----	----	294549	WR
7667	153	constant amplitude	201	0.1	10	----	----	382826	WR
7668	484	constant amplitude	327	0.1	10	----	----	936	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7669	485	constant amplitude	206	0.1	10	----	----	286613	WR
7670	486	constant amplitude	413	0.1	10	----	----	1119	WR
7671	282	constant amplitude	413	0.1	10	----	----	85	WR
7672	284	constant amplitude	242	0.1	10	----	----	109547	WR
7673	297	constant amplitude	414	0.1	10	----	----	491	WR
7674	298	constant amplitude	414	0.1	10	----	----	356	WR
7675	302	constant amplitude	241	0.1	10	----	----	54487	WR
7676	305	constant amplitude	207	0.1	10	----	----	121190	WR
7677	308	constant amplitude	412	0.1	10	----	----	91	WR
7678	309	constant amplitude	207	0.1	10	----	----	373306	WR
7679	313	constant amplitude	414	0.1	10	----	----	429	WR
7680	321	constant amplitude	328	0.1	10	----	----	2611	WR
7681	323	constant amplitude	242	0.1	10	----	----	16884	WR
7682	325	constant amplitude	327	0.1	10	----	----	8653	WR
7683	326	constant amplitude	241	0.1	10	----	----	104679	WR
7684	344	constant amplitude	183	0.1	10	----	runout	561088	WR
7685	363	constant amplitude	327	0.1	10	----	----	3139	WR
7686	376	constant amplitude	327	0.1	10	----	----	1706	WR
7687	378	constant amplitude	207	0.1	10	----	----	261287	WR
7688	391	constant amplitude	207	0.1	10	----	----	421272	WR
7689	433	constant amplitude	414	0.1	10	----	----	757	WR
7690	434	constant amplitude	331	0.1	10	----	----	3744	WR
7691	435	constant amplitude	241	0.1	10	----	----	181518	WR
7692	436	constant amplitude	206	0.1	10	----	----	1137595	WR
7693	554	constant amplitude	326	0.1	10	----	----	763	WR
7694	577	constant amplitude	410	0.1	10	----	----	310	WR
7695	578	constant amplitude	410	0.1	10	----	----	274	WR
7696	579	constant amplitude	410	0.1	10	----	----	283	WR
7697	580	constant amplitude	410	0.1	10	----	----	334	WR
7698	581	constant amplitude	324	0.1	10	----	----	4375	WR
7699	582	constant amplitude	325	0.1	10	----	----	4190	WR
7700	583	constant amplitude	325	0.1	10	----	----	2620	WR
7701	584	constant amplitude	325	0.1	10	----	----	1306	WR
7702	585	constant amplitude	240	0.1	10	----	----	186268	WR
7703	586	constant amplitude	240	0.1	10	----	----	89527	WR
7704	587	constant amplitude	240	0.1	10	----	----	35109	WR
7705	588	constant amplitude	240	0.1	10	----	----	187293	WR
7706	589	constant amplitude	206	0.1	10	----	----	697446	WR
7707	590	constant amplitude	206	0.1	10	----	----	436185	WR
7708	591	constant amplitude	206	0.1	10	----	----	732874	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7709	592	constant amplitude	206	0.1	10	----	----	366748	WR
7710	607	constant amplitude	326	0.1	10	----	----	1690	WR
7711	609	constant amplitude	240	0.1	10	----	----	58826	WR
7712	611	constant amplitude	206	0.1	10	----	----	318890	WR
7713	129	constant amplitude	414	0.1	10	----	----	78	WR
7714	130	constant amplitude	414	0.1	10	----	----	149	WR
7715	131	constant amplitude	241	0.1	10	----	----	141377	WR
7716	138	constant amplitude	241	0.1	10	----	----	143456	WR
7717	147	constant amplitude	241	0.1	10	----	----	31943	WR
7718	148	constant amplitude	414	0.1	10	----	----	155	WR
7719	160	constant amplitude	207	0.1	10	----	----	495397	WR
7720	161	constant amplitude	328	0.1	10	----	----	1722	WR
7721	168	constant amplitude	328	0.1	10	----	----	744	WR
7722	169	constant amplitude	207	0.1	10	----	----	588371	WR
7723	171	constant amplitude	328	0.1	10	----	----	3152	WR
7724	172	constant amplitude	414	0.1	10	----	----	162	WR
7725	174	constant amplitude	207	0.1	10	----	----	37855	WR
7726	606	constant amplitude	414	0.1	10	----	----	286	load10
7727	608	constant amplitude	328	0.1	10	----	----	1794	load10
7728	610	constant amplitude	241	0.1	10	----	----	43618	load10
7729	605	constant amplitude	414	0.1	10	----	----	783	load10
7730	616	constant amplitude	328	0.1	10	----	----	1081	load10
7731	618	constant amplitude	328	0.1	10	----	----	769	load10
7732	620	constant amplitude	414	0.1	10	----	----	234	load10
7733	622	constant amplitude	414	0.1	10	----	----	290	load10
7734	624	constant amplitude	414	0.1	10	----	----	161	load10
7735	626	constant amplitude	207	0.1	10	----	----	496355	load10
7736	628	constant amplitude	207	0.1	10	----	----	129134	load10
7737	630	constant amplitude	241	0.1	10	----	----	57742	load10
7738	633	constant amplitude	241	0.1	10	----	----	43491	load10
7739	612	constant amplitude	207	0.1	10	----	----	418886	load10
7740	617	constant amplitude	328	0.1	10	----	----	2433	load10
7741	619	constant amplitude	328	0.1	10	----	----	2329	load10
7742	621	constant amplitude	414	0.1	10	----	----	180	load10
7743	623	constant amplitude	414	0.1	10	----	----	311	load10
7744	625	constant amplitude	207	0.1	10	----	----	41493	load10
7745	627	constant amplitude	207	0.1	10	----	----	598609	load10
7746	629	constant amplitude	207	0.1	10	----	----	78888	load10
7747	632	constant amplitude	241	0.1	10	----	----	37576	load10
7748	634	constant amplitude	241	0.1	10	----	----	163745	load10

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7749	744	constant amplitude	414	0.1	10	----	----	642	load10
7750	745	constant amplitude	328	0.1	10	----	----	1290	load10
7751	746	constant amplitude	241	0.1	10	----	----	31733	load10
7752	747	constant amplitude	207	0.1	10	----	----	544532	load10
7753	784	constant amplitude	414	0.1	10	----	----	343	load10
7754	788	constant amplitude	328	0.1	10	----	----	815	load10
7755	792	constant amplitude	241	0.1	10	----	----	115525	load10
7756	636	constant amplitude	241	0.5	10	----	----	464516	load11
7757	638	constant amplitude	241	0.5	10	----	----	460884	load11
7758	640	constant amplitude	241	0.5	10	----	----	98521	load11
7759	642	constant amplitude	328	0.5	10	----	----	5801	load11
7760	644	constant amplitude	328	0.5	10	----	----	24381	load11
7761	648	constant amplitude	414	0.5	10	----	----	438	load11
7762	650	constant amplitude	414	0.5	10	----	----	1169	load11
7763	641	constant amplitude	328	0.5	10	----	----	7421	load11
7764	643	constant amplitude	328	0.5	10	----	----	6548	load11
7765	645	constant amplitude	328	0.5	10	----	----	19568	load11
7766	647	constant amplitude	414	0.5	10	----	----	2609	load11
7767	649	constant amplitude	414	0.5	10	----	----	2507	load11
7768	651	constant amplitude	414	0.5	10	----	----	1475	load11
7769	672	constant amplitude	328	0.5	10	----	----	1400	load11
7770	673	constant amplitude	241	0.5	10	----	----	100193	load11
7771	717	constant amplitude	414	0.5	10	----	----	2886	load11
7772	718	constant amplitude	414	0.5	10	----	----	1412	load11
7773	719	constant amplitude	328	0.5	10	----	----	21037	load11
7774	720	constant amplitude	328	0.5	10	----	----	120101	load11
7775	721	constant amplitude	241	0.5	10	----	----	272818	load11
7776	722	constant amplitude	241	0.5	10	----	----	545546	load11
7777	785	constant amplitude	414	0.5	10	----	----	400	load11
7778	789	constant amplitude	328	0.5	10	----	----	11812	load11
7779	796	constant amplitude	-277	10	10	----	----	11608	load10
7780	797	constant amplitude	-277	10	10	----	----	2463	load10
7781	798	constant amplitude	-276	10	10	----	----	2727	load10
7782	799	constant amplitude	-280	10	10	----	----	5904	load10
7783	800	constant amplitude	-277	10	10	----	----	5123	load10
7784	801	constant amplitude	-242	10	10	----	----	379064	load10
7785	802	constant amplitude	-244	10	10	----	----	54873	load10
7786	803	constant amplitude	-243	10	10	----	----	11145	load10
7787	804	constant amplitude	-243	10	10	----	----	11738	load10
7788	805	constant amplitude	-245	10	10	----	----	21240	load10

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7789	806	constant amplitude	-259	10	10	----	----	5010	load10
7790	807	constant amplitude	-211	10	10	----	----	487946	load10
7791	808	constant amplitude	-214	10	10	----	----	993821	load10
7792	809	constant amplitude	-208	10	10	----	----	1859843	load10
7793	810	constant amplitude	-208	10	10	----	----	1747111	load10
7794	811	constant amplitude	-209	10	10	----	----	1464645	load10
7795	813	constant amplitude	-276	10	10	----	----	2469	load10
7796	814	constant amplitude	-276	10	10	----	----	4353	load10
7797	816	constant amplitude	-277	10	10	----	----	3850	load10
7798	817	constant amplitude	-277	10	10	----	----	15393	load10
7799	819	constant amplitude	-243	10	10	----	----	14172	load10
7800	820	constant amplitude	-243	10	10	----	----	36657	load10
7801	821	constant amplitude	-241	10	10	----	----	6704	load10
7802	822	constant amplitude	-242	10	10	----	----	9235	load10
7803	823	constant amplitude	-243	10	10	----	----	67973	load10
7804	825	constant amplitude	-208	10	10	----	----	1505733	load10
7805	826	constant amplitude	-208	10	10	----	----	1980344	load10
7806	827	constant amplitude	-210	10	10	----	----	1037244	load10
7807	828	constant amplitude	-215	10	10	----	----	1508674	load10
7808	829	constant amplitude	-208	10	10	----	----	842537	load10
7809	920	constant amplitude	-324	10	10	----	----	131	load10
7810	921	constant amplitude	-322	10	10	----	----	364	load10
7811	922	constant amplitude	-323	10	10	----	----	415	load10
7812	923	constant amplitude	-335	10	10	----	----	334	load10
7813	924	constant amplitude	-323	10	10	----	----	533	load10
7814	925	constant amplitude	-322	10	10	----	----	1019	load10
7815	926	constant amplitude	-322	10	10	----	----	327	load10
7816	927	constant amplitude	-333	10	10	----	----	322	load10
7817	928	constant amplitude	-323	10	10	----	----	433	load10
7818	929	constant amplitude	-325	10	10	----	----	104	load10
7819	855	constant amplitude	-278	10	10	----	----	4063	load10
7820	856	constant amplitude	-277	10	10	----	----	4410	load10
7821	857	constant amplitude	-275	10	10	----	----	1957	load10
7822	858	constant amplitude	-277	10	10	----	----	8288	load10
7823	859	constant amplitude	-276	10	10	----	----	10692	load10
7824	860	constant amplitude	-208	10	10	----	----	2021912	load10
7825	861	constant amplitude	-216	10	10	----	----	943072	load10
7826	862	constant amplitude	-208	10	10	----	----	205084	load10
7827	863	constant amplitude	-216	10	10	----	----	1884110	load10
7828	864	constant amplitude	-207	10	10	----	----	235297	load10

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7829	335	constant amplitude	413	0.5	10	----	----	4701	WR
7830	336	constant amplitude	327	0.5	10	----	----	32173	WR
7831	337	constant amplitude	241	0.5	10	----	----	1469317	WR
7832	343	constant amplitude	241	0.5	10	----	----	350682	WR
7833	346	constant amplitude	413	0.5	10	----	----	3836	WR
7834	347	constant amplitude	327	0.5	10	----	----	20006	WR
7835	408	constant amplitude	413	0.5	10	----	----	2290	WR
7836	409	constant amplitude	327	0.5	10	----	----	49288	WR
7837	412	constant amplitude	242	0.5	10	----	----	829489	WR
7838	416	constant amplitude	327	0.5	10	----	----	74500	WR
7839	417	constant amplitude	413	0.5	10	----	----	4100	WR
7840	418	constant amplitude	242	0.5	10	----	----	1559097	WR
7841	426	constant amplitude	248	0.5	10	----	----	808064	WR
7842	429	constant amplitude	327	0.5	10	----	----	33362	WR
7843	431	constant amplitude	412	0.5	10	----	----	2469	WR
7844	487	constant amplitude	326	0.5	10	----	----	21452	WR
7845	488	constant amplitude	241	0.5	10	----	----	156860	WR
7846	556	constant amplitude	326	0.5	10	----	----	15905	WR
7847	557	constant amplitude	326	0.5	10	----	----	38319	WR
7848	558	constant amplitude	327	0.5	10	----	----	8357	WR
7849	559	constant amplitude	326	0.5	10	----	----	31685	WR
7850	560	constant amplitude	326	0.5	10	----	----	21025	WR
7851	561	constant amplitude	326	0.5	10	----	----	48516	WR
7852	562	constant amplitude	326	0.5	10	----	----	24391	WR
7853	563	constant amplitude	241	0.5	10	----	----	1051280	WR
7854	564	constant amplitude	241	0.5	10	----	----	1988538	WR
7855	565	constant amplitude	241	0.5	10	----	----	1119777	WR
7856	566	constant amplitude	241	0.5	10	----	----	280171	WR
7857	568	constant amplitude	240	0.5	10	----	----	1749635	WR
7858	569	constant amplitude	241	0.5	10	----	----	763276	WR
7859	570	constant amplitude	241	0.5	10	----	----	2470072	WR
7860	571	constant amplitude	412	0.5	10	----	----	1652	WR
7861	572	constant amplitude	411	0.5	10	----	----	2513	WR
7862	573	constant amplitude	411	0.5	10	----	----	2519	WR
7863	576	constant amplitude	412	0.5	10	----	----	2755	WR
7864	793	constant amplitude	239	0.5	10	----	----	334060	WR
7865	1038	constant amplitude	183	-1	5	----	----	5556	revers
7866	1039	constant amplitude	145	-1	5	----	----	93249	revers
7867	1040	constant amplitude	147	-1	5	----	----	74482	revers
7868	1041	constant amplitude	111	-1	5	----	----	1313993	revers

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7869	1042	constant amplitude	110	-1	5	----	----	902103	revers
7870	1043	constant amplitude	112	-1	5	----	----	1814761	revers
7871	1044	constant amplitude	178	-1	5	----	----	4861	revers
7872	1045	constant amplitude	148	-1	5	----	----	62837	revers
7873	1046	constant amplitude	111	-1	5	----	----	785091	revers
7874	1047	constant amplitude	146	-1	5	----	----	93636	revers
7875	1048	constant amplitude	156	-1	5	----	----	17397	revers
7876	1049	constant amplitude	114	-1	5	----	----	2108317	revers
7877	1050	constant amplitude	178	-1	5	----	----	6004	revers
7878	1051	constant amplitude	145	-1	5	----	----	57737	revers
7879	892	constant amplitude	-276	2	10	----	----	130733	load11
7880	893	constant amplitude	-276	2	8	----	runout	62258	load11
7881	894	constant amplitude	-276	2	10	----	----	158396	load11
7882	895	constant amplitude	-276	2	10	----	----	1442932	load11
7883	896	constant amplitude	-276	2	10	----	----	162400	load11
7884	897	constant amplitude	-276	2	10	----	----	46304	load11
7885	898	constant amplitude	-276	2	10	----	----	192595	load11
7886	899	constant amplitude	-276	2	10	----	----	48990	load11
7887	905	constant amplitude	-276	2	10	----	----	1190152	load11
7888	906	constant amplitude	-241	2	10	----	runout	10000000	load11
7889	907	constant amplitude	-276	2	10	----	runout	4950838	load11
7890	908	constant amplitude	-276	2	10	----	runout	11829100	load11
7891	909	constant amplitude	-276	2	10	----	----	2738468	load11
7892	910	constant amplitude	-276	2	10	----	----	4297	load11
7893	919	constant amplitude	-207	2	10	----	runout	4013900	load11
8500	901	constant amplitude	-241	2	10	----	----	2659182	load 11
7894	132	2 block, 10H/1000L	414 / 241	0.1	10	72	7000	7072	WR
7895	133	2 block, 10H/334L	414 / 241	0.1	10	40	1002	1042	WR
7896	134	2 block, 10H/3000L	414 / 241	0.1	10	54	15000	15054	WR
7897	135	2 block, 10H/112L	414 / 241	0.1	10	230	2464	2694	WR
7898	136	2 block, 10H/9000L	414 / 241	0.1	10	13	9000	9013	WR
7899	137	2 block, 10H/10L	414 / 241	0.1	10	130	120	250	WR
7900	142	2 block, 10H/9000L	414 / 241	0.1	10	22	18000	18022	WR
7901	143	2 block, 10H/1000L	414 / 241	0.1	10	60	5000	5060	WR
7902	144	2 block, 10H/334L	414 / 241	0.1	10	117	3674	3791	WR
7903	145	2 block, 10H/112L	414 / 241	0.1	10	91	1008	1099	WR
7904	146	2 block, 10H/10L	414 / 241	0.1	10	286	280	566	WR
7905	149	2 block, 10H/52L	414 / 241	0.1	10	182	936	1118	WR
7906	150	2 block, 10H/52L	414 / 241	0.1	10	195	988	1183	WR
7907	154	2 block, 10H/1000L	328 / 207	0.1	10	432	43000	43432	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7908	155	2 block, 10H/112L	328 / 207	0.1	10	1077	11984	13061	WR
7909	156	2 block, 10H/9000L	328 / 207	0.1	10	120	92379	92499	WR
7910	157	2 block, 10H/3000L	328 / 207	0.1	10	554	162287	162841	WR
7911	158	2 block, 10H/10L	328 / 207	0.1	10	1840	1830	3670	WR
7912	159	2 block, 10H/334L	328 / 207	0.1	10	1062	35404	36466	WR
7913	162	2 block, 10H/1000L	328 / 207	0.1	10	1432	143000	144432	WR
7914	163	2 block, 10H/112L	328 / 207	0.1	10	2119	23632	25751	WR
7915	164	2 block, 10H/9000L	328 / 207	0.1	10	270	239206	239476	WR
7916	165	2 block, 10H/3000L	328 / 207	0.1	10	406	120000	120406	WR
7917	166	2 block, 10H/10L	328 / 207	0.1	10	4249	4240	8489	WR
7918	167	2 block, 10H/334L	328 / 207	0.1	10	932	31062	31994	WR
7919	170	2 block, 10H/10L	328 / 207	0.1	10	3552	3550	7102	WR
7920	175	2 block, 10H/667L	328 / 207	0.1	10	987	65366	66353	WR
7921	176	2 block, 10H/1000L	328 / 207	0.1	10	349	34000	34349	WR
7922	177	2 block, 10H/1000L	328 / 207	0.1	10	656	65000	65656	WR
7923	178	2 block, 10H/1000L	328 / 207	0.1	10	197	19000	19197	WR
7924	180	2 block, 20H/10L	328 / 207	0.1	10	2418	1200	3618	WR
7925	181	2 block, 10H/250L	328 / 207	0.1	10	2207	54750	56957	WR
7926	182	2 block, 10H/40L	328 / 207	0.1	10	2419	9640	12059	WR
7927	183	2 block, 10H/1000L	328 / 207	0.1	10	510	50906	51416	WR
7928	184	2 block, 10H/667L	328 / 207	0.1	10	359	23345	23704	WR
7929	186	2 block, 10H/33000L	328 / 207	0.1	10	106	330000	330106	WR
7930	187	2 block, 10H/33000L	328 / 207	0.1	10	42	165000	165042	WR
7931	188	2 block, 10H/50000L	328 / 207	0.1	10	30	139982	140012	WR
7932	189	2 block, 10H/60000L	328 / 207	0.1	10	50	295894	295944	WR
7933	190	2 block, 10H/20000L	328 / 207	0.1	10	150	297672	297822	WR
7934	191	2 block, 10H/50000L	328 / 207	0.1	10	30	101013	101043	WR
7935	192	2 block, 10H/33000L	328 / 207	0.1	10	50	158561	158611	WR
7936	193	2 block, 10H/60000L	328 / 207	0.1	10	20	91339	91359	WR
7937	194	2 block, 10H/1000L	328 / 241	0.1	10	140	13016	13156	WR
7938	195	2 block, 10H/3000L	328 / 241	0.1	10	150	44460	44610	WR
7939	196	2 block, 10H/5000L	328 / 241	0.1	10	40	17361	17401	WR
7940	198	2 block, 10H/500L	328 / 241	0.1	10	250	12114	12364	WR
7941	199	2 block, 10H/100L	328 / 241	0.1	10	364	3600	3964	WR
7942	200	2 block, 10H/10L	328 / 241	0.1	10	1357	1350	2707	WR
7943	201	2 block, 10H/500L	328 / 241	0.1	10	100	4774	4874	WR
7944	202	2 block, 10H/1000L	328 / 241	0.1	10	100	9359	9459	WR
7945	203	2 block, 10H/5000L	328 / 241	0.1	10	40	15564	15604	WR
7946	204	2 block, 10H/3000L	328 / 241	0.1	10	110	30522	30632	WR
7947	205	2 block, 0H/100L	241	0.1	10	----	----	15680	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7948	206	2 block, 10H/0L	328	0.1	10	----	----	1339	WR
7949	211	2 block, 10H/10L	414 / 241	0.1	10	98	90	188	WR
7950	212	2 block, 10H/10L	414 / 241	0.1	10	72	70	142	WR
7951	215	2 block, 10H/9000L	414 / 241	0.1	10	17	9000	9017	WR
7952	275	2 block, 10H/112L	414 / 241	0.1	10	274	3024	3298	WR
7953	300	2 block, 10H/9000L	414 / 241	0.1	10	40	27155	27195	WR
7954	304	2 block, 10H/112L	414 / 241	0.1	10	312	3472	3784	WR
7955	307	2 block, 10H/90L	414 / 241	0.1	10	44	360	404	WR
7956	209	2 block, 10H/10L	328 / 241	0.1	10	583	580	1163	WR
7957	210	2 block, 10H/10L	328 / 241	0.1	10	1815	1810	3625	WR
7958	217	2 block, 10H/3000L	328 / 241	0.1	10	60	17063	17123	WR
7959	213	2 block, 10H/0L	328	0.1	10	----	----	3306	WR
7960	214	2 block, 10H/0L	328	0.1	10	----	----	2078	WR
7961	207	2 block, 10H/10L	328 / 207	0.1	10	2163	2160	4323	WR
7962	208	2 block, 10H/10L	328 / 207	0.1	10	2326	2320	4646	WR
7963	216	2 block, 10H/9000L	328 / 207	0.1	10	85	72000	72085	WR
7964	218	2 block, 10H/3000L	328 / 207	0.1	10	110	31739	31849	WR
7965	219	2 block, 10H/5000L	328 / 207	0.1	10	80	39441	39521	WR
7966	229	2 block, 10H/60000L	328 / 207	0.1	10	20	61684	61704	WR
7967	230	2 block, 10H/50000L	328 / 207	0.1	10	70	319095	319165	WR
7968	232	2 block, 10H/9000L	328 / 207	0.1	10	100	81000	81100	WR
7969	233	2 block, 10H/50000L	328 / 207	0.1	10	50	202625	202675	WR
7970	234	2 block, 10H/9000L	328 / 207	0.1	10	210	180000	180210	WR
7971	235	2 block, 10H/33000L	328 / 207	0.1	10	30	82555	82585	WR
7972	246	2 block, 10H/10L	241 / 207	0.1	10	67370	67365	134735	WR
7973	247	2 block, 10H/9000L	241 / 207	0.1	10	600	535083	535683	WR
7974	248	2 block, 10H/33000L	241 / 207	0.1	10	100	307196	307296	WR
7975	249	2 block, 10H/60000L	241 / 207	0.1	10	30	137575	137605	WR
7976	250	2 block, 10H/9000L	241 / 207	0.1	10	580	518806	519386	WR
7977	251	2 block, 10H/60000L	241 / 207	0.1	10	40	198456	198496	WR
7978	252	2 block, 10H/10L	241 / 207	0.1	10	37306	37300	74606	WR
7979	253	2 block, 10H/9000L	241 / 207	0.1	10	410	366273	366683	WR
7980	254	2 block, 10H/33000L	241 / 207	0.1	10	90	274261	274351	WR
7981	255	2 block, 20H/10L	241 / 207	0.1	10	26342	13170	39512	WR
7982	256	2 block, 10H/10L	414 / 328	0.1	10	42	40	82	WR
7983	257	2 block, 10H/1000L	414 / 328	0.1	10	10	603	613	WR
7984	258	2 block, 10H/100L	414 / 328	0.1	10	20	145	165	WR
7985	259	2 block, 10H/100L	414 / 328	0.1	10	39	300	339	WR
7986	260	2 block, 10H/1000L	414 / 328	0.1	10	20	1268	1288	WR
7987	310	2 block, 10H/10L	414 / 328	0.1	10	141	140	281	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
7988	311	2 block, 10H/90L	414 / 328	0.1	10	173	1530	1703	WR
7989	312	2 block, 10H/990L	414 / 328	0.1	10	10	517	527	WR
7990	261	2 block, 10H/10L	328 / 207	0.1	10	519	510	1029	WR
7991	263	2 block, 1H/100L	328 / 207	0.1	10	942	94100	95042	WR
7992	264	2 block, 1H/100L	328 / 207	0.1	10	90	8900	8990	WR
7993	265	2 block, 10H/10000L	328 / 207	0.1	10	120	110187	110307	WR
7994	267	2 block, 10H/1000L	328 / 207	0.1	10	340	33037	33377	WR
7995	279	2 block, 10H/5000L	328 / 241	0.1	10	150	71692	71842	WR
7996	280	2 block, 10H/1000L	328 / 241	0.1	10	80	7892	7972	WR
7997	350	2 block, 10H/10L	328 / 241	0.1	10	5749	5740	11489	WR
7998	351	2 block, 10H/90L	328 / 241	0.1	10	1899	17010	18909	WR
7999	281	2 block, 10H/100L	328 / 207	0.1	10	2543	25400	27943	WR
8000	276	2 block, 10H/1000L	328 / 207	0.1	10	359	35000	35359	WR
8001	287	2 block, 10H/1000L	328 / 207	0.1	10	408	40800	41208	random1
8002	288	2 block, 10H/1000L	328 / 207	0.1	10	288	28840	29128	random1
8003	289	2 block, 1H/100L	328 / 207	0.1	10	81	8100	8181	onecycle
8004	290	2 block, 10H/1000L	328 / 207	0.1	10	175	17448	17623	random1
8005	291	2 block, 10H/1000L	328 / 207	0.1	10	610	60710	61320	WR
8006	294	2 block, 10H/1000L	328 / 207	0.1	10	540	53027	53567	WR
8007	295	2 block, 10H/1000L	328 / 207	0.1	10	442	44166	44608	random1
8008	314	2 block, 10H/1000L	328 / 207	0.1	10	335	33528	33863	random2
8009	315	2 block, 10H/10L	328 / 207	0.1	10	2174	2170	4344	WR
8010	316	2 block, 10H/90L	328 / 207	0.1	10	1762	15840	17602	WR
8011	317	2 block, 10H/1000L	328 / 207	0.1	10	464	46400	46864	random2
8012	320	2 block, 1H/100L	328 / 207	0.1	10	301	30100	30401	onecycle
8013	322	2 block, 10H/1000L	328 / 207	0.1	10	441	44103	44544	random2
8014	324	2 block, 1H/100L	328 / 207	0.1	10	127	12700	12827	onecycle
8015	327	2 block, 10H/1000L	328 / 207	0.1	10	480	48211	48691	random2
8016	328	2 block, 10H/1000L	328 / 207	0.1	10	799	79000	79799	WR
8017	330	2 block, 10H/1000L	328 / 207	0.1	10	379	37932	38311	random2
8018	331	2 block, 10H/1000L	328 / 207	0.1	10	980	98000	98980	random3
8019	332	2 block, 1H/100L	328 / 207	0.1	10	278	27800	28078	onecycle
8020	333	2 block, 10H/1000L	328 / 207	0.1	10	510	51000	51510	random3
8021	334	2 block, 10H/1000L	328 / 207	0.1	10	591	59082	59673	random2
8022	353	2 block, 10H/1000L	328 / 207	0.1	10	350	35002	35352	random3
8023	354	2 block, 10H/1000L	328 / 207	0.1	10	832	83248	84080	random2
8024	368	2 block, 10H/1000L	328 / 207	0.1	10	551	55063	55614	onecycle
8025	369	2 block, 10H/1000L	328 / 207	0.1	10	312	31000	31312	WR
8026	370	2 block, 1H/100L	328 / 207	0.1	10	584	58400	58984	onecycle
8027	371	2 block, 1H/100L	328 / 207	0.1	10	257	25700	25957	onecycle

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8028	372	2 block, 10H/1000L	328 / 207	0.1	10	750	75006	75756	random3
8029	373	2 block, 10H/1000L	328 / 207	0.1	10	479	47874	48353	random3
8030	374	2 block, 10H/1000L	328 / 207	0.1	10	1470	146350	147820	WR
8031	375	2 block, 10H/1000L	328 / 207	0.1	10	561	56122	56683	random3
8032	377	2 block, 1H/100L	328 / 207	0.1	10	670	67000	67670	onecycle
8033	379	2 block, 1H/100L	328 / 207	0.1	10	606	60600	61206	onecycle
8034	380	2 block, 10H/1000L	328 / 207	0.1	10	699	69875	70574	random3
8035	381	2 block, 10H/1000L	328 / 207	0.1	10	630	63002	63632	random3
8036	382	2 block, 1H/100L	328 / 207	0.1	10	301	30100	30401	onecycle
8037	384	2 block, 1H/100L	328 / 207	0.1	10	681	68100	68781	onecycle
8038	385	2 block, 10H/1000L	328 / 207	0.1	10	364	36388	36752	random3
8039	386	2 block, 10H/1000L	328 / 207	0.1	10	454	45000	45454	WR
8040	387	2 block, 10H/1000L	328 / 207	0.1	10	460	46001	46461	random3
8041	388	2 block, 1H/100L	328 / 207	0.1	10	1698	169800	171498	onecycle
8042	389	2 block, 10H/1000L	328 / 207	0.1	10	510	51005	51515	random3
8043	390	2 block, 10H/1000L	328 / 207	0.1	10	869	86907	87776	random3
8044	392	2 block, 1H/100L	328 / 207	0.1	10	755	75500	76255	onecycle
8045	393	2 block, 1H/100L	328 / 207	0.1	10	407	40700	41107	onecycle
8046	394	2 block, 10H/1000L	328 / 207	0.1	10	720	71039	71759	WR
8047	395	2 block, 1H/100L	328 / 207	0.1	10	306	30600	30906	onecycle
8048	396	2 block, 10H/1000L	328 / 207	0.1	10	800	80004	80804	random3
8049	397	2 block, 10H/1000L	328 / 207	0.1	10	993	99000	99993	WR
8050	398	2 block, 10H/1000L	328 / 207	0.1	10	369	36860	37229	random3
8051	399	2 block, 1H/100L	328 / 207	0.1	10	598	59800	60398	WR
8052	411	2 block, 10H/1000L	328 / 207	0.1	10	460	46000	46460	random3
8053	432	2 block, 1H/100L	328 / 207	0.1	0.1	447	44600	45047	WR
8054	437	2 block, 10H/1000L	328 / 207	0.1	10	1282	128000	129282	WR
8055	277	2 block, 10H/1000L	241 / 207	0.1	10	1320	131237	132557	WR
8056	278	2 block, 10H/100L	241 / 207	0.1	10	34940	349366	384306	WR
8057	285	2 block, 10H/1000L	241 / 207	0.1	10	7060	706997	714057	WR
8058	299	2 block, 10H/990L	241 / 207	0.1	10	5970	590898	596868	WR
8059	301	2 block, 10H/90L	241 / 207	0.1	10	10170	91462	101632	WR
8060	303	2 block, 10H/49990L	241 / 207	0.1	10	60	264911	264971	WR
8061	318	2 block, 10H/90L	241 / 207	0.1	10	1610	14403	16013	WR
8062	319	2 block, 10H/990L	241 / 207	0.1	10	1980	195842	197822	WR
8063	339	2 block, 10H/1000L	328 / 207	0.5	10	1630	16200	17830	WR
8064	348	2 block, 10H/1000L	328 / 207	0.5	10	1790	179000	180790	WR
8065	352	2 block, 10H/1000L	328 / 207	0.5	10	1710	171000	172710	WR
8066	400	2 block, 10H/10L	414 / 328	0.5	10	1292	1290	2582	WR
8067	401	2 block, 10H/50L	414 / 328	0.5	10	879	4350	5229	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8068	402	2 block, 10H/100L	414 / 328	0.5	10	560	5576	6136	WR
8069	403	2 block, 10H/1000L	414 / 328	0.5	10	165	16000	16165	WR
8070	404	2 block, 10H/10L	414 / 328	0.5	10	2266	2260	4526	WR
8071	405	2 block, 10H/50L	414 / 328	0.5	10	2352	11750	14102	WR
8072	406	2 block, 10H/100L	414 / 328	0.5	10	872	8700	9572	WR
8073	407	2 block, 10H/1000L	414 / 328	0.5	10	240	23256	23496	WR
8074	413	2 block, 10H/10L	414 / 241	0.5	10	3233	3230	6463	WR
8075	414	2 block, 10H/1000L	414 / 241	0.5	10	267	26000	26267	WR
8076	415	2 block, 10H/10000L	414 / 241	0.5	10	175	170000	170175	WR
8077	419	2 block, 10H/10000L	414 / 241	0.5	10	91	90000	90091	WR
8078	420	2 block, 10H/1000L	414 / 241	0.5	10	258	25000	25258	WR
8079	421	2 block, 10H/10L	414 / 241	0.5	10	2800	2800	5600	WR
8080	422	2 block, 10H/10L	328 / 241	0.5	10	14325	14320	28645	WR
8081	423	2 block, 10H/100L	328 / 241	0.5	10	22439	224300	246739	WR
8082	424	2 block, 10H/1000L	328 / 241	0.5	10	1939	193000	194939	WR
8083	425	2 block, 10H/1000L	328 / 241	0.5	10	1481	148000	149481	WR
8084	427	2 block, 10H/100L	328 / 241	0.5	10	16397	163900	180297	WR
8085	428	2 block, 10H/10L	328 / 241	0.5	10	47833	47830	95663	WR
8086	345	2 block, 10H/90L	328 / 241	0.5	10	80180	721620	801800	WR
8087	438	2 block, 10H/1000L	328 / 207	0.1	10	432	43206	43638	rand2
8088	444	2 block, 10H/1000L	414 / 261	0.1	10	24	2383	2407	rand5
8089	445	2 block, 10H/1000L	328 / 207	0.1	10	156	15629	15785	rand5
8090	446	2 block, 10H/1000L	328 / 207	0.1	10	291	29134	29425	rand5
8091	447	2 block, 10H/1000L	328 / 207	0.1	10	810	81086	81896	rand5
8092	448	2 block, 10H/1000L	328 / 207	0.1	10	231	23134	23365	rand5
8093	449	2 block, 10H/1000L	328 / 207	0.1	10	331	33134	33465	rand5
8094	450	2 block, 10H/1000L	328 / 207	0.1	10	201	20127	20328	rand5
8095	451	2 block, 10H/1000L	328 / 207	0.1	10	136	13576	13712	rand5
8096	452	2 block, 10H/1000L	328 / 207	0.1	10	369	36851	37220	rand5
8097	453	2 block, 10H/1000L	328 / 207	0.1	10	125	12469	12594	rand5
8098	454	2 block, 10H/1000L	328 / 207	0.1	10	509	50912	51421	rand5
8099	455	2 block, 10H/1000L	328 / 207	0.1	10	289	28912	29201	rand5
8100	456	2 block, 10H/1000L	328 / 207	0.1	10	269	26851	27120	rand5
8101	457	2 block, 10H/1000L	328 / 207	0.1	10	122	12209	12331	rand5
8102	483	2 block, 10H/1000L	328 / 207	0.1	10	349	34949	35298	rand5
8103	526	2 block, 10H/1000L	328 / 207	0.1	10	470	46982	47452	rand5
8104	529	2 block, 10H/1000L	328 / 207	0.1	10	119	11851	11970	rand5
8105	532	2 block, 10H/1000L	328 / 207	0.1	10	131	13134	13265	rand5
8106	535	2 block, 10H/1000L	328 / 207	0.1	10	105	10548	10653	rand5
8107	538	2 block, 10H/1000L	328 / 207	0.1	10	141	14087	14228	rand5

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8108	541	2 block, 10H/1000L	328 / 207	0.1	10	122	12209	12331	rand5
8109	544	2 block, 10H/1000L	328 / 207	0.1	10	53	5342	5395	rand5
8110	547	2 block, 10H/1000L	328 / 207	0.1	10	463	46342	46805	rand5
8111	550	2 block, 10H/1000L	328 / 207	0.1	10	70	6982	7052	rand5
8112	553	2 block, 10H/1000L	328 / 207	0.1	10	206	20576	20782	rand5
8113	480	2 block, 1H/100L	328 / 207	0.1	10	469	46900	47369	onecycle
8114	481	2 block, 10H/1000L	328 / 207	0.1	10	528	52876	53404	random2
8115	482	2 block, 10H/1000L	328 / 207	0.1	10	320	32007	32327	random3
8116	524	2 block, 1H/100L	328 / 207	0.1	10	227	22674	22901	onecycle
8117	525	2 block, 10H/1000L	328 / 207	0.1	10	340	34008	34348	load5
8118	527	2 block, 1H/100L	328 / 207	0.1	10	393	39300	39693	onecycle
8119	528	2 block, 10H/1000L	328 / 207	0.1	10	192	19209	19401	load5
8120	530	2 block, 1H/100L	328 / 207	0.1	10	233	23300	23533	onecycle
8121	531	2 block, 10H/1000L	328 / 207	0.1	10	1150	115005	116155	load5
8122	533	2 block, 1H/100L	328 / 207	0.1	10	550	55019	55569	onecycle
8123	534	2 block, 10H/1000L	328 / 207	0.1	10	240	24008	24248	load5
8124	536	2 block, 1H/100L	328 / 207	0.1	10	261	26153	26414	onecycle
8125	537	2 block, 10H/1000L	328 / 207	0.1	10	220	22001	22221	load5
8126	539	2 block, 1H/100L	328 / 207	0.1	10	469	46900	47369	onecycle
8127	540	2 block, 10H/1000L	328 / 207	0.1	10	58	5834	5892	load5
8128	542	2 block, 1H/100L	328 / 207	0.1	10	239	23900	24139	onecycle
8129	543	2 block, 10H/1000L	328 / 207	0.1	10	260	25951	26211	load5
8130	545	2 block, 1H/100L	328 / 207	0.1	10	241	24060	24301	onecycle
8131	546	2 block, 10H/1000L	328 / 207	0.1	10	179	17908	18087	load5
8132	548	2 block, 1H/100L	328 / 207	0.1	10	198	19800	19998	onecycle
8133	549	2 block, 10H/1000L	328 / 207	0.1	10	310	31007	31317	load5
8134	551	2 block, 1H/100L	328 / 207	0.1	10	138	13767	13905	onecycle
8135	552	2 block, 10H/1000L	328 / 207	0.1	10	254	25393	25647	load5
8136	593	2 block, 10H/1000L	328 / 207	0.1	10	1020	102006	103026	load5
8137	595	2 block, 10H/1000L	328 / 207	0.1	10	410	41006	41416	load5
8138	597	2 block, 10H/1000L	328 / 207	0.1	10	1850	185004	186854	load5
8139	599	2 block, 10H/1000L	328 / 207	0.1	10	2120	212007	214127	load5
8140	601	2 block, 10H/1000L	328 / 207	0.1	10	490	49001	49491	load5
8141	603	2 block, 10H/1000L	328 / 207	0.1	10	500	50008	50508	load5
8142	594	2 block, 10H/1000L	328 / 207	0.1	10	379	37000	37379	WR
8143	596	2 block, 10H/1000L	328 / 207	0.1	10	310	30570	30880	WR
8144	598	2 block, 10H/1000L	328 / 207	0.1	10	324	32000	32324	WR
8145	600	2 block, 10H/1000L	328 / 207	0.1	10	853	85000	85853	WR
8146	602	2 block, 10H/1000L	328 / 207	0.1	10	310	30952	31262	WR
8147	604	2 block, 10H/1000L	328 / 207	0.1	10	390	38919	39309	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8148	657	2 block, 10H/90L	414 / 241	0.5	10	490	4411	4901	load12
8149	658	2 block, 10H/90L	414 / 241	0.5	10	1130	10178	11308	load12
8150	665	2 block, 10H/90L	328 / 241	0.5	10	3230	29073	32303	load15
8151	659	2 block, 10H/990L	414 / 241	0.5	10	310	30695	31005	load13
8152	660	2 block, 10H/990L	414 / 241	0.5	10	440	43565	44005	load13
8153	662	2 block, 10H/990L	328 / 241	0.5	10	2800	277206	280006	load14
8154	663	2 block, 10H/990L	328 / 241	0.5	10	3360	332645	336005	load14
8155	669	2 block, 10H/990L	414 / 241	0.5	10	70	6934	7004	load18
8156	667	2 block, 10H/9990L	414 / 241	0.5	10	120	119888	120008	load16
8157	668	2 block, 10H/9990L	414 / 241	0.5	10	41	41388	41429	load16
8158	670	2 block, 10H/9990L	414 / 241	0.5	10	70	69935	70005	load16
8159	674	2 block, 10H/9990L	328 / 241	0.5	10	350	349656	350006	load17
8160	675	2 block, 10H/9990L	328 / 241	0.5	10	160	160773	160933	load17
8161	836	2 block, 10H/1000L	-276 / -207	10	10	3030	303000	306030	comp1
8162	837	2 block, 10H/1000L	-276 / -207	10	10	2500	250000	252500	comp1
8163	838	2 block, 10H/1000L	-276 / -207	10	10	2200	220005	222205	comp1
8164	839	2 block, 10H/1000L	-276 / -207	10	10	4590	459006	463596	comp1
8165	840	2 block, 10H/100L	-276 / -207	10	10	2651	26508	29159	comp2
8166	841	2 block, 10H/100L	-276 / -207	10	10	8311	83107	91418	comp2
8167	842	2 block, 10H/100L	-276 / -207	10	10	9890	98903	108793	comp2
8168	843	2 block, 10H/100L	-276 / -207	10	10	10920	109206	120126	comp2
8169	844	2 block, 10H/10L	-276 / -207	10	10	1684	1684	3368	comp3
8170	845	2 block, 10H/10L	-276 / -207	10	10	11151	11151	22302	comp3
8171	846	2 block, 10H/10L	-276 / -207	10	10	4374	4374	8748	comp3
8172	847	2 block, 10H/10000L	-276 / -207	10	10	290	290007	290297	comp4
8173	848	2 block, 10H/10000L	-276 / -207	10	10	330	330003	330333	comp4
8174	849	2 block, 10H/10000L	-276 / -207	10	10	2030	2030002	2032032	comp4
8175	850	2 block, 10H/1000L	-276 / -207	10	10	630	63000	63630	comp1
8176	851	2 block, 10H/1000L	-276 / -207	10	10	7430	743010	750440	comp1
8177	852	2 block, 10H/1000L	-276 / -207	10	10	4780	478000	482780	comp1
8178	853	2 block, 10H/1000L	-276 / -207	10	10	400	40007	40407	comp1
8179	854	2 block, 10H/1000L	-276 / -207	10	10	680	68001	68681	comp1
8180	870	2 block, 10H/10L	-276 / -207	10	10	1171	1170	2341	comp3
8181	871	2 block, 10H/10L	-276 / -207	10	10	2675	2674	5349	comp3
8182	872	2 block, 10H/10L	-276 / -207	10	10	1685	1684	3369	comp3
8183	873	2 block, 10H/10L	-276 / -207	10	10	3362	3362	6724	comp3
8184	874	2 block, 10H/10L	-276 / -207	10	10	9812	9812	19624	comp3
8185	875	2 block, 10H/10000L	-276 / -207	10	10	990	990000	990990	comp4
8186	876	2 block, 10H/10000L	-276 / -207	10	10	1398	1397653	1399051	comp4
8187	877	2 block, 10H/10000L	-276 / -207	10	10	153	155364	155517	comp4

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8188	878	2 block, 10H/10000L	-276 / -207	10	10	728	727806	728534	comp4
8189	879	2 block, 10H/10000L	-276 / -207	10	10	640	640008	640648	comp4
8190	930	2 block, 10H/100L	-328 / -207	10	8	324	3200	3524	r10ld1
8191	931	2 block, 10H/100L	-328 / -207	10	8	1080	10800	11880	r10ld1
8192	932	2 block, 10H/100L	-328 / -207	10	8	670	6700	7370	r10ld1
8193	933	2 block, 10H/100L	-328 / -207	10	8	212	2100	2312	r10ld1
8194	934	2 block, 10H/100L	-328 / -207	10	8	1815	18100	19915	r10ld1
8195	935	2 block, 10H/100L	-328 / -207	10	8	427	4200	4627	r10ld1
8196	936	2 block, 10H/100L	-328 / -207	10	8	462	4600	5062	r10ld1
8197	937	2 block, 10H/100L	-328 / -207	10	8	877	8700	9577	r10ld1
8198	938	2 block, 10H/100L	-328 / -207	10	8	90	900	990	r10ld1
8199	939	2 block, 10H/100L	-328 / -207	10	8	505	5000	5505	r10ld1
8200	940	2 block, 10H/10L	-328 / -207	10	8	546	540	1086	r10ld2
8201	941	2 block, 10H/10L	-328 / -207	10	8	2053	2050	4103	r10ld2
8202	942	2 block, 10H/10L	-328 / -207	10	8	1235	1230	2465	r10ld2
8203	943	2 block, 10H/10L	-328 / -207	10	8	452	450	902	r10ld2
8204	944	2 block, 10H/10L	-328 / -207	10	8	1402	1400	2802	r10ld2
8205	945	2 block, 10H/10L	-328 / -207	10	8	334	330	664	r10ld2
8206	946	2 block, 10H/10L	-328 / -207	10	8	525	520	1045	r10ld2
8207	947	2 block, 10H/10L	-328 / -207	10	8	239	230	469	r10ld2
8208	948	2 block, 10H/10L	-328 / -207	10	8	690	690	1380	r10ld2
8209	950	2 block, 10H/10000L	-328 / -207	10	8	21	20000	20021	r10ld3
8210	951	2 block, 10H/10000L	-328 / -207	10	8	139	130000	130139	r10ld3
8211	952	2 block, 10H/10000L	-328 / -207	10	8	688	680000	680688	r10ld3
8212	953	2 block, 10H/10000L	-328 / -207	10	8	272	270000	270272	r10ld3
8213	956	2 block, 10H/10000L	-328 / -207	10	8	73	70000	70073	r10ld3
8214	957	2 block, 10H/10000L	-328 / -207	10	8	12	10000	10012	r10ld3
8215	958	2 block, 10H/10000L	-328 / -207	10	8	31	30000	30031	r10ld3
8216	959	2 block, 10H/10000L	-328 / -207	10	8	80	80004	80084	r10ld3
8217	960	2 block, 10H/1000L	-328 / -207	10	8	171	17000	17171	load5
8218	961	2 block, 10H/1000L	-328 / -207	10	8	128	12000	12128	load5
8219	962	2 block, 10H/1000L	-328 / -207	10	8	84	8000	8084	load5
8220	963	2 block, 10H/1000L	-328 / -207	10	8	244	24000	24244	load5
8221	964	2 block, 10H/1000L	-328 / -207	10	8	87	8000	8087	load5
8222	965	2 block, 10H/1000L	-328 / -207	10	8	254	25000	25254	load5
8223	966	2 block, 10H/1000L	-328 / -207	10	8	69	6000	6069	load5
8224	967	2 block, 10H/1000L	-328 / -207	10	8	81	8000	8081	load5
8225	968	2 block, 10H/1000L	-328 / -207	10	8	1220	122000	123220	load5
8226	969	2 block, 10H/1000L	-328 / -207	10	8	591	590000	590591	load5
8227	1087	2 block, 10H/10L	172 / 103	-1	5	25430	25420	50850	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8228	1088	2 block, 10H/10L	172 / 103	-1	5	16536	16530	33066	WR
8229	1089	2 block, 10H/10L	172 / 103	-1	5	11467	11460	22927	WR
8230	1090	2 block, 10H/10L	172 / 103	-1	5	8779	8770	17549	WR
8231	1091	2 block, 10H/10L	172 / 103	-1	5	18018	18010	36028	WR
8232	1092	2 block, 10H/10L	172 / 103	-1	5	16674	16670	33344	WR
8233	1093	2 block, 10H/10L	172 / 103	-1	5	24781	24780	49561	WR
8234	1094	2 block, 10H/10L	172 / 103	-1	5	34040	34030	68070	WR
8235	1095	2 block, 10H/10L	172 / 103	-1	5	19245	19240	38485	WR
8236	1096	2 block, 10H/10L	172 / 103	-1	5	22190	22180	44370	WR
8237	1097	2 block, 10H/100L	172 / 103	-1	5	7581	75800	83381	WR
8238	1098	2 block, 10H/100L	172 / 103	-1	5	14380	143781	158161	WR
8239	1099	2 block, 10H/100L	172 / 103	-1	5	6405	64000	70405	WR
8240	1100	2 block, 10H/100L	172 / 103	-1	5	13142	131400	144542	WR
8241	1101	2 block, 10H/100L	172 / 103	-1	5	7191	71900	79091	WR
8242	1102	2 block, 10H/100L	172 / 103	-1	5	5291	52900	58191	WR
8243	1103	2 block, 10H/100L	172 / 103	-1	5	10150	101488	111638	WR
8244	1104	2 block, 10H/100L	172 / 103	-1	5	4283	42800	47083	WR
8245	1105	2 block, 10H/100L	172 / 103	-1	5	7100	70018	77118	WR
8246	1106	2 block, 10H/100L	172 / 103	-1	5	4003	40000	44003	WR
8247	1107	2 block, 10H/1000L	172 / 103	-1	5	1671	167000	168671	WR
8248	1108	2 block, 10H/1000L	172 / 103	-1	5	2470	246518	248988	WR
8249	1109	2 block, 10H/1000L	172 / 103	-1	5	2425	242000	244425	WR
8250	1110	2 block, 10H/1000L	172 / 103	-1	5	1641	164000	165641	WR
8251	1111	2 block, 10H/1000L	172 / 103	-1	5	2836	283000	285836	WR
8252	1112	2 block, 10H/1000L	172 / 103	-1	5	3848	384000	387848	WR
8253	1113	2 block, 10H/1000L	172 / 103	-1	5	2621	262000	264621	WR
8254	1114	2 block, 10H/1000L	172 / 103	-1	5	2600	259000	261600	WR
8255	1115	2 block, 10H/1000L	172 / 103	-1	5	2110	210319	212429	WR
8256	1116	2 block, 10H/1000L	172 / 103	-1	5	1050	104409	105459	WR
8257	1117	2 block, 10H/10000L	172 / 103	-1	5	860	853094	853954	WR
8258	1118	2 block, 10H/10000L	172 / 103	-1	5	430	423228	423658	WR
8259	1119	2 block, 10H/10000L	172 / 103	-1	5	960	950993	951953	WR
8260	1120	2 block, 10H/10000L	172 / 103	-1	5	760	750198	750958	WR
8261	1121	2 block, 10H/10000L	172 / 103	-1	5	770	762262	763032	WR
8262	1122	2 block, 10H/10000L	172 / 103	-1	5	550	542948	543498	WR
8263	1123	2 block, 10H/10000L	172 / 103	-1	5	750	749389	750139	WR
8264	1124	2 block, 10H/10000L	172 / 103	-1	5	690	683831	684521	WR
8265	1125	2 block, 10H/10000L	172 / 103	-1	5	470	464239	464709	WR
8266	1126	2 block, 10H/10000L	172 / 103	-1	5	700	600096	600796	WR
3 Block Tests, Tests numbered 8267 through 8277									

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8267	179	10H/100M/1000L	414/328/207	0.1	10	62	6000	6662	WR
8268	439	10H/10M/100L	414/328/241	0.1	10	394	390	4684	WR
8269	440	10M/10H/100L	328/414/241	0.1	10	820	811	9731	WR
8270	441	10H/100L/10M	414/241/328	0.1	10	219	2100	2529	WR
8271	442	10H/10M/100L	414/328/241	0.1	10	270	260	3130	WR
8272	443	100L/10M/10H	241/328/414	0.1	10	4200	420	5037	WR
8273	489	10H/10M/100L	414/328/241	0.1	10	113	110	1323	WR
8274	490	10M/10H/100L	328/414/241	0.1	10	180	174	2054	WR
8275	491	100L/10M/10H	241/328/414	0.1	10	160	1600	1920	WR
8276	492	10M/10H/100L	414/328/241	0.1	10	120	123	1443	WR
8277	493	100L/10M/10H	241/328/414	0.1	10	160	1634	1954	WR
Wisperx and Modified Spectrum Tests									
8278	654	Wisperx	410	SP	10	----	----	14090	Wisperx
8279	656	Wisperx	353	SP	10	----	----	13404	Wisperx
8280	676	Wisperx	411	SP	10	----	----	12832	Wisperx
8281	661	Wisperx	326	SP	10	----	----	160725	Wisperx
8282	713	WisxR01	394	SP	10	----	----	893	WisxR01
8283	714	WisxR01	389	SP	10	----	----	504	WisxR01
8284	723	WisxR01	403	SP	10	----	----	1227	WisxR01
8285	740	WisxR01	395	SP	10	----	----	620	WisxR01
8286	741	WisxR01	396	SP	10	----	----	1120	WisxR01
8287	742	WisxR01	394	SP	10	----	----	818	WisxR01
8288	743	WisxR01	395	SP	10	----	----	624	WisxR01
8289	786	WisxR01	405	SP	10	----	----	1713	WisxR01
8290	711	WisxR01	322	SP	10	----	----	3963	WisxR01
8291	712	WisxR01	321	SP	10	----	----	4457	WisxR01
8292	724	WisxR01	325	SP	10	----	----	4330	WisxR01
8293	726	WisxR01	322	SP	10	----	----	3973	WisxR01
8294	735	WisxR01	322	SP	10	----	----	1977	WisxR01
8295	736	WisxR01	321	SP	10	----	----	11721	WisxR01
8296	737	WisxR01	322	SP	10	----	----	6742	WisxR01
8297	738	WisxR01	322	SP	10	----	----	14445	WisxR01
8298	790	WisxR01	321	SP	10	----	----	12294	WisxR01
8299	709	WisxR01	237	SP	10	----	----	392963	WisxR01
8300	710	WisxR01	237	SP	10	----	----	77859	WisxR01
8301	716	WisxR01	238	SP	10	----	----	201697	WisxR01
8302	725	WisxR01	239	SP	10	----	----	128215	WisxR01
8303	727	WisxR01	237	SP	10	----	----	491135	WisxR01
8304	728	WisxR01	237	SP	10	----	----	116302	WisxR01
8305	729	WisxR01	237	SP	10	----	----	153229	WisxR01

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8306	730	WisxR01	237	SP	10	----	----	165568	WisxR01
8307	794	WisxR01	236	SP	10	----	----	104636	WisxR01
8308	707	WisxR01	204	SP	10	----	----	2502591	WisxR01
8309	708	WisxR01	203	SP	10	----	----	1523103	WisxR01
8310	715	WisxR01	204	SP	10	----	----	1231745	WisxR01
8311	732	WisxR01	203	SP	10	----	----	609578	WisxR01
8312	733	WisxR01	203	SP	10	----	----	202727	WisxR01
8313	734	WisxR01	204	SP	10	----	----	2231997	WisxR01
8314	677	WisxR05	408	SP	10	----	----	1874	WisxR05
8315	678	WisxR05	409	SP	10	----	----	2812	WisxR05
8316	679	WisxR05	409	SP	10	----	----	6270	WisxR05
8317	680	WisxR05	408	SP	10	----	----	2768	WisxR05
8318	682	WisxR05	409	SP	10	----	----	2680	WisxR05
8319	683	WisxR05	408	SP	10	----	----	2102	WisxR05
8320	684	WisxR05	410	SP	10	----	----	1397	WisxR05
8321	685	WisxR05	399	SP	10	----	----	956	WisxR05
8322	686	WisxR05	410	SP	10	----	----	3915	WisxR05
8323	687	WisxR05	325	SP	10	----	----	40997	WisxR05
8324	688	WisxR05	324	SP	10	----	----	51690	WisxR05
8325	689	WisxR05	324	SP	10	----	----	28166	WisxR05
8326	690	WisxR05	324	SP	10	----	----	34678	WisxR05
8327	691	WisxR05	324	SP	10	----	----	42728	WisxR05
8328	692	WisxR05	324	SP	10	----	----	42077	WisxR05
8329	693	WisxR05	326	SP	10	----	----	204617	WisxR05
8330	694	WisxR05	325	SP	10	----	----	64030	WisxR05
8331	695	WisxR05	324	SP	10	----	----	61941	WisxR05
8332	696	WisxR05	324	SP	10	----	----	24102	WisxR05
8333	697	WisxR05	239	SP	10	----	----	1268170	WisxR05
8334	698	WisxR05	239	SP	10	----	----	851414	WisxR05
8335	700	WisxR05	240	SP	10	----	----	5040003	WisxR05
8336	701	WisxR05	240	SP	10	----	----	3466288	WisxR05
8337	702	WisxR05	240	SP	10	----	----	1620900	WisxR05
8338	703	WisxR05	239	SP	10	----	----	1002695	WisxR05
8339	704	WisxR05	240	SP	10	----	----	993446	WisxR05
8340	705	WisxR05	239	SP	10	----	----	1130037	WisxR05
8341	706	WisxR05	239	SP	10	----	----	2387020	WisxR05
8342	787	WisxR05	409	SP	10	----	----	1349	WisxR05
8343	791	WisxR05	323	SP	10	----	----	63945	WisxR05
8344	795	WisxR05	238	SP	10	----	----	862547	WisxR05
8345	748	Wisxmix	407	SP	10	----	----	2211	Wisxmix

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8346	749	Wisxmix	407	SP	10	----	----	3313	Wisxmix
8347	750	Wisxmix	407	SP	10	----	----	1744	Wisxmix
8348	751	Wisxmix	408	SP	10	----	----	2260	Wisxmix
8349	752	Wisxmix	407	SP	10	----	----	2058	Wisxmix
8350	753	Wisxmix	407	SP	10	----	----	5679	Wisxmix
8351	754	Wisxmix	408	SP	10	----	----	3634	Wisxmix
8352	755	Wisxmix	407	SP	10	----	----	1705	Wisxmix
8353	757	Wisxmix	323	SP	10	----	----	8425	Wisxmix
8354	758	Wisxmix	323	SP	10	----	----	17202	Wisxmix
8355	759	Wisxmix	323	SP	10	----	----	17170	Wisxmix
8356	760	Wisxmix	323	SP	10	----	----	49795	Wisxmix
8357	761	Wisxmix	322	SP	10	----	----	15763	Wisxmix
8358	762	Wisxmix	322	SP	10	----	----	29281	Wisxmix
8359	763	Wisxmix	323	SP	10	----	----	9075	Wisxmix
8360	764	Wisxmix	323	SP	10	----	----	45756	Wisxmix
8361	766	Wisxmix	237	SP	10	----	----	259709	Wisxmix
8362	767	Wisxmix	237	SP	10	----	----	625695	Wisxmix
8363	768	Wisxmix	237	SP	10	----	----	157203	Wisxmix
8364	769	Wisxmix	237	SP	10	----	----	373607	Wisxmix
8365	770	Wisxmix	237	SP	10	----	----	477747	Wisxmix
8366	771	Wisxmix	237	SP	10	----	----	165811	Wisxmix
8367	772	Wisxmix	237	SP	10	----	----	534391	Wisxmix
8368	773	Wisxmix	237	SP	10	----	----	763579	Wisxmix
8369	775	Wisxmix	204	SP	10	----	----	2883840	Wisxmix
8370	776	Wisxmix	202	SP	10	----	----	1085994	Wisxmix
8371	777	Wisxmix	204	SP	10	----	----	1803131	Wisxmix
8372	778	Wisxmix	204	SP	10	----	----	1005992	Wisxmix
8373	779	Wisxmix	205	SP	10	----	----	496982	Wisxmix
8374	780	Wisxmix	203	SP	10	----	----	1701443	Wisxmix
8375	781	Wisxmix	204	SP	10	----	----	2392836	Wisxmix
8376	782	Wisxmix	203	SP	10	----	----	2079241	Wisxmix
8377	970	Wispk	403	SP	10	----	----	3844	Wispk
8378	971	Wispk	341	SP	10	----	----	1276	Wispk
8379	972	Wispk	343	SP	10	----	----	2325	Wispk
8380	973	Wispk	344	SP	10	----	----	2448	Wispk
8381	974	Wispk	407	SP	10	----	----	3130	Wispk
8382	975	Wispk	403	SP	10	----	----	4044	Wispk
8383	976	Wispk	403	SP	10	----	----	2806	Wispk
8384	977	Wispk	405	SP	10	----	----	5722	Wispk
8385	978	Wispk	406	SP	10	----	----	3233	Wispk

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8386	979	Wispk	402	SP	10	----	----	3203	Wispk
8387	980	Wispk	298	SP	10	----	----	167885	Wispk
8388	981	Wispk	298	SP	10	----	----	155850	Wispk
8389	982	Wispk	297	SP	10	----	----	195616	Wispk
8390	983	Wispk	301	SP	10	----	----	86293	Wispk
8391	984	Wispk	297	SP	10	----	----	298800	Wispk
8392	985	Wispk	298	SP	10	----	----	169839	Wispk
8393	986	Wispk	297	SP	10	----	----	68426	Wispk
8394	987	Wispk	297	SP	10	----	----	231019	Wispk
8395	988	Wispk	297	SP	10	----	----	144430	Wispk
8396	989	Wispk	297	SP	10	----	----	80980	Wispk
8397	990	Wispk	254	SP	10	----	----	195751	Wispk
8398	991	Wispk	255	SP	10	----	----	598438	Wispk
8399	992	Wispk	256	SP	10	----	----	876955	Wispk
8400	993	Wispk	253	SP	10	----	----	1231928	Wispk
8401	995	Wispk	254	SP	10	----	----	312744	Wispk
8402	996	Wispk	259	SP	10	----	----	432307	Wispk
8403	997	Wispk	256	SP	10	----	----	912240	Wispk
8404	998	Wispk	255	SP	10	----	----	680774	Wispk
8405	999	Wispk	256	SP	10	----	----	248429	Wispk
8406	1000	Wispk	335	SP	10	----	----	14371	Wispk
8407	1001	Wispk	335	SP	10	----	----	26045	Wispk
8408	1002	Wispk	341	SP	10	----	----	18334	Wispk
8409	1003	Wispk	340	SP	10	----	----	24906	Wispk
8410	1004	Wispk	339	SP	10	----	----	6048	Wispk
8411	1005	Wispk	341	SP	10	----	----	13058	Wispk
8412	1006	Wispk	343	SP	10	----	----	24196	Wispk
8413	1007	Wispk	185	SP	10	----	----	14130978	Wispk
8414	1016	Wispk	185	SP	10	----	----	12289518	Wispk
Residual Strength Tests, DD16									
8415	236	constant amplitude	207	0.1	10	----	----	446342	WR
8416	237	constant amplitude	207	0.1	10	----	----	200016	WR
8417	237r	one cycle	417	13	*	----	----	1	WR
8418	238	constant amplitude	207	0.1	10	----	----	100009	WR
8419	238r	one cycle	452	13	*	----	----		WR
8420	239	constant amplitude	207	0.1	10	----	----	111838	WR
8421	240	constant amplitude	207	0.1	10	----	----	300010	WR
8422	240r	one cycle	451	13	*	----	----	1	WR
8423	241	constant amplitude	207	0.1	10	----	----	130521	WR
8424	242	constant amplitude	207	0.1	10	----	----	133659	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8425	243	constant amplitude	207	0.1	10	----	----	100010	WR
8426	243r	one cycle	403	13	*	----	----	1	WR
8427	244	constant amplitude	207	0.1	10	----	----	38964	WR
8428	245	constant amplitude	207	0.1		----	----	50008	WR
8429	245r	one cycle	450	13	*	----	----	1	WR
8430	459	constant amplitude	414	0.1	10	----	----	100	WR
8431	459r	one cycle	654	13	*	----	----		WR
8432	460	constant amplitude	414	0.1	10	----	----	478	WR
8433	461	constant amplitude	414	0.1	10	----	----	810	WR
8434	462	constant amplitude	414	0.1	10	----	----	100	WR
8435	462r	one cycle	661	13	*	----	----	1	WR
8436	463	constant amplitude	414	0.1	10	----	----	100	WR
8437	462r	one cycle	660	13	*	----	----	1	WR
8438	464	constant amplitude	328	0.1	10	----	----	1000	WR
8439	464r	one cycle	661	13	*	----	----	1	WR
8440	465	constant amplitude	328	0.1	10	----	----	7752	WR
8441	466	constant amplitude	328	0.1	10	----	----	1000	WR
8442	466r	one cycle	589	13	*	----	----	1	WR
8443	467	constant amplitude	328	0.1	10	----	----	9811	WR
8444	468	constant amplitude	328	0.1	10	----	----	1000	WR
8445	468r	one cycle	571	13	*	----	----	1	WR
8446	469	constant amplitude	241	0.1	10	----	----	10000	WR
8447	469r	one cycle	650	13	*	----	----	1	WR
8448	470	constant amplitude	241	0.1	10	----	----	100000	WR
8449	470r	one cycle	590	13	*	----	----	1	WR
8450	471	constant amplitude	241	0.1	10	----	----	100000	WR
8451	471r	one cycle	639	13	*	----	----	1	WR
8452	472	constant amplitude	241	0.1	10	----	----	10000	WR
8453	472r	one cycle	649	13	*	----	----	1	WR
8454	473	constant amplitude	241	0.1	10	----	----	10000	WR
8455	473r	one cycle	654	13	*	----	----	1	WR
8456	475	constant amplitude	328	0.1	10	----	----	10000	WR
8457	475r	one cycle	633	13	*	----	----	1	WR
8458	476	constant amplitude	241	0.1	10	----	----	100000	WR
8459	476r	one cycle	599	13	*	----	----	1	WR
8460	477	constant amplitude	414	0.1	10	----	----	1000	WR
8461	477r	one cycle	662	13	*	----	----	1	WR
8462	494	constant amplitude	328	0.5	10	----	----	9596	WR
8463	495	constant amplitude	328	0.5	10	----	----	9872	WR
8464	496	constant amplitude	328	0.5	10	----	----	12289	WR

Test and coupon #		Comment	Maximum Stress, MPa	R value	Freq Hz	# High Cycles	# Low Cycles	Total Cycles	program
8465	497	constant amplitude	328	0.5	10	----	----	8981	WR
8466	498	constant amplitude	328	0.5	10	----	----	8899	WR
8467	499	constant amplitude	328	0.5	10	----	----	32810	WR
8468	500	constant amplitude	328	0.5	10	----	----	20000	WR
8469	500r	one cycle	560	13	*	----	----	1	WR
8470	501	constant amplitude	328	0.5	10	----	----	10000	WR
8471	501r	one cycle	501	13	*	----	----	1	WR
8472	502	constant amplitude	328	0.5	10	----	----	12442	WR
8473	503	constant amplitude	328	0.5	10	----	----	5336	WR
8474	504	constant amplitude	328	0.5	10	----	----	10000	WR
8475	504r	one cycle	585	13	*	----	----	1	WR
8476	505	constant amplitude	328	0.5	10	----	----	9800	WR
8477	506	constant amplitude	328	0.5	10	----	----	11920	WR
8478	507	constant amplitude	328	0.5	10	----	----	3769	WR
8479	508	constant amplitude	328	0.5	10	----	----	8254	WR
8480	509	constant amplitude	328	0.5	10	----	----	20000	WR
8481	509r	one cycle	469	13	*	----	----	1	WR
8482	510	constant amplitude	328	0.5	10	----	----	10000	WR
8483	510r	one cycle	498	13	*	----	----	1	WR
8484	511	constant amplitude	328	0.5	10	----	----	18330	WR
8485	512	constant amplitude	328	0.5	10	----	----	8643	WR
8486	513	constant amplitude	328	0.5	10	----	----	10000	WR
8487	513r	one cycle	590	13	*	----	----	1	WR
8488	514	constant amplitude	328	0.5	10	----	----	11418	WR
8489	515	constant amplitude	328	0.5	10	----	----	10814	WR
8490	516	constant amplitude	328	0.5	10	----	----	7732	WR
8491	517	constant amplitude	328	0.5	10	----	----	13968	WR
8492	518	constant amplitude	328	0.5	10	----	----	8684	WR
8493	519	constant amplitude	328	0.5	10	----	----	10000	WR
8494	519r	one cycle	540	13	*	----	----	1	WR
8495	520	constant amplitude	328	0.5	10	----	----	7107	WR
8496	521	constant amplitude	328	0.5	10	----	----	7189	WR
8497	522	constant amplitude	328	0.5	10	----	----	10000	WR
8498	522r	one cycle	403	13	*	----	----	1	WR
8499	523	constant amplitude	328	0.5	10	----	----	13784	WR

APPENDIX B

CONSTANT AMPLITUDE FATIGUE TEST SUMMARY

Description of Table Headings for Appendix B

1) Test No. - Coupon identification number.

2) Total Cycles - The total number of cycles of the test.

3) Log Cycles - Natural logarithm of the number of cycles.

4) MPa, Max Stress - Maximum stress applied to the test coupon.

5) Log Stress - Natural logarithm of the maximum stress.

6) Exponent All Data - a linear residual strength degradation equation was used in conjunction with an exponential fit of the fatigue data including all tests (as opposed to excluding the static tests).

7) Power All Data - a linear residual strength degradation equation was used in conjunction with a power fit of the fatigue data including all tests (as opposed to excluding the static tests).

8) Power-Static - a nonlinear residual strength degradation equation was used in conjunction with a power fit of the fatigue data, excluding the static tests.

9) Exponent-Static - a nonlinear residual strength degradation equation was used in conjunction with an exponential fit of the fatigue data, excluding the static tests.

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
R=0.1								
274	1	0.000	680.4	2.833	604.0	635.3	648.6	537.0
283	1	0.000	649.5	2.813	604.0	635.3	648.6	537.0
296	1	0.000	489.1	2.689	604.0	635.3	648.6	537.0
306	1	0.000	673.1	2.828	604.0	635.3	648.6	537.0
329	1	0.000	542.6	2.734	604.0	635.3	648.6	537.0
349	1	0.000	558.5	2.747	604.0	635.3	648.6	537.0
383	1	0.000	652.4	2.815	604.0	635.3	648.6	537.0
410	1	0.000	638.3	2.805	604.0	635.3	648.6	537.0
430	1	0.000	598.9	2.777	604.0	635.3	648.6	537.0
474	1	0.000	629.5	2.799	604.0	635.3	648.6	537.0
479	1	0.000	657.4	2.818	604.0	635.3	648.6	537.0
635	1	0.000	670.1	2.826	604.0	635.3	648.6	537.0
646	1	0.000	569.3	2.755	604.0	635.3	648.6	537.0
652	1	0.000	619.3	2.792	604.0	635.3	648.6	537.0
653	1	0.000	676.4	2.830	604.0	635.3	648.6	537.0
655	1	0.000	688.8	2.838	604.0	635.3	648.6	537.0
666	1	0.000	670.9	2.827	604.0	635.3	648.6	537.0
671	1	0.000	687.3	2.837	604.0	635.3	648.6	537.0
739	1	0.000	644.3	2.809	604.0	635.3	648.6	537.0
726a	1	0.000	647.8	2.811	604.0	635.3	648.6	537.0
129	78	1.892	409.1	2.612	460.7	434.7	439.8	422.7
282	85	1.929	413.3	2.616	457.9	431.4	436.5	420.5
308	91	1.959	412.6	2.616	455.7	428.9	433.8	418.7
130	149	2.173	405.6	2.608	439.5	410.8	415.2	405.7
148	155	2.190	414.0	2.617	438.2	409.4	413.7	404.7
624	161	2.207	411.8	2.615	436.9	408.1	412.3	403.7
172	162	2.210	407.0	2.610	436.7	407.9	412.1	403.5
621	180	2.255	410.5	2.613	433.3	404.1	408.2	400.8
620	234	2.369	410.0	2.613	424.6	395.0	398.8	393.9
578	274	2.438	410.6	2.613	419.4	389.6	393.2	389.7
579	283	2.452	410.2	2.613	418.4	388.5	392.1	388.9
606	286	2.456	412.2	2.615	418.0	388.1	391.7	388.6
622	290	2.462	410.0	2.613	417.6	387.7	391.2	388.3
577	310	2.491	410.2	2.613	415.4	385.4	388.9	386.5
623	311	2.493	410.1	2.613	415.3	385.3	388.8	386.4
580	334	2.524	410.5	2.613	412.9	382.9	386.3	384.6
784	343	2.535	406.6	2.609	412.1	382.1	385.5	383.9
298	356	2.551	414.2	2.617	410.8	380.8	384.1	382.9
313	429	2.632	414.7	2.618	404.7	374.7	377.8	378.0

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
297	491	2.691	413.8	2.617	400.3	370.3	373.3	374.4
744	642	2.807	393.8	2.595	391.5	361.8	364.5	367.4
168	744	2.872	315.1	2.498	386.6	357.1	359.7	363.5
433	757	2.879	414.4	2.617	386.0	356.6	359.1	363.1
554	763	2.883	326.1	2.513	385.8	356.3	358.9	362.9
618	769	2.886	324.9	2.512	385.5	356.1	358.6	362.7
605	783	2.894	411.1	2.614	384.9	355.5	358.1	362.2
788	815	2.911	324.1	2.511	383.6	354.3	356.8	361.2
616	1081	3.034	324.8	2.512	374.3	345.7	347.9	353.7
745	1290	3.110	322.9	2.509	368.5	340.4	342.5	349.1
584	1306	3.116	325.3	2.512	368.1	340.0	342.1	348.8
206	1339	3.127	321.6	2.507	367.3	339.3	341.3	348.1
607	1690	3.228	325.8	2.513	359.6	332.5	334.3	342.0
376	1706	3.232	327.6	2.515	359.3	332.2	334.0	341.8
161	1722	3.236	327.8	2.516	359.0	331.9	333.8	341.5
608	1794	3.254	325.4	2.512	357.7	330.8	332.5	340.5
140	1914	3.282	323.1	2.509	355.6	328.9	330.6	338.8
214	2078	3.318	318.7	2.503	352.9	326.6	328.2	336.6
139	2297	3.361	330.0	2.519	349.6	323.7	325.3	334.0
619	2329	3.367	325.7	2.513	349.1	323.3	324.9	333.6
617	2433	3.386	325.2	2.512	347.7	322.1	323.6	332.5
321	2611	3.417	328.3	2.516	345.3	320.1	321.6	330.6
583	2620	3.418	324.9	2.512	345.2	320.0	321.5	330.5
363	3139	3.497	327.0	2.515	339.3	315.0	316.4	325.8
171	3152	3.499	322.7	2.509	339.2	314.9	316.2	325.7
213	3306	3.519	324.0	2.511	337.6	313.6	314.9	324.4
434	3744	3.573	331.2	2.520	333.5	310.2	311.4	321.2
582	4190	3.622	325.2	2.512	329.8	307.2	308.3	318.2
581	4375	3.641	324.7	2.511	328.4	306.0	307.1	317.1
325	8653	3.937	327.3	2.515	306.0	288.4	289.0	299.2
205	15680	4.195	238.1	2.377	286.4	273.8	274.1	283.6
323	16884	4.227	242.2	2.384	284.0	272.1	272.3	281.6
746	31733	4.502	237.9	2.376	263.3	257.5	257.4	265.1
147	31943	4.504	241.5	2.383	263.0	257.4	257.2	264.9
587	35109	4.545	240.2	2.381	259.9	255.3	255.1	262.4
632	37576	4.575	239.5	2.379	257.7	253.8	253.5	260.7
632	37576	4.575	239.5	2.379	257.7	253.8	253.5	260.7
174	37855	4.578	236.4	2.374	257.5	253.6	253.4	260.5
625	41493	4.618	205.5	2.313	254.4	251.6	251.3	258.1
633	43491	4.638	239.8	2.380	252.9	250.5	250.2	256.8

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
610	43618	4.640	240.1	2.380	252.8	250.5	250.2	256.7
302	54487	4.736	241.6	2.383	245.5	245.7	245.3	250.9
630	57742	4.761	239.3	2.379	243.6	244.4	244.0	249.4
609	58826	4.770	240.5	2.381	243.0	244.0	243.6	248.9
629	78888	4.897	205.7	2.313	233.3	237.9	237.3	241.2
586	89527	4.952	240.0	2.380	229.2	235.3	234.6	237.9
326	104679	5.020	241.3	2.383	224.0	232.1	231.4	233.8
284	109547	5.040	241.7	2.383	222.5	231.2	230.5	232.6
792	115525	5.063	237.6	2.376	220.8	230.1	229.4	231.2
305	121190	5.083	206.7	2.315	219.2	229.1	228.4	229.9
305	121190	5.083	206.7	2.315	219.2	229.1	228.4	229.9
628	129134	5.111	205.4	2.313	217.1	227.9	227.1	228.3
131	141377	5.150	241.3	2.383	214.1	226.1	225.3	225.9
138	143456	5.157	241.6	2.383	213.7	225.8	225.0	225.5
634	163745	5.214	239.8	2.380	209.3	223.2	222.3	222.0
634	163745	5.214	239.8	2.380	209.3	223.2	222.3	222.0
435	181518	5.259	240.8	2.382	205.9	221.2	220.3	219.3
585	186268	5.270	239.8	2.380	205.1	220.7	219.8	218.7
588	187293	5.273	239.9	2.380	204.9	220.6	219.7	218.5
378	261287	5.417	207.2	2.316	194.0	214.3	213.3	209.8
151	274271	5.438	205.0	2.312	192.4	213.4	212.3	208.5
485	286613	5.457	206.6	2.315	190.9	212.6	211.5	207.4
152	294549	5.469	202.4	2.306	190.0	212.1	211.0	206.6
611	318890	5.504	206.2	2.314	187.4	210.6	209.5	204.6
309	373306	5.572	207.4	2.317	182.2	207.8	206.6	200.4
153	382826	5.583	201.1	2.303	181.4	207.3	206.1	199.8
612	418886	5.622	206.1	2.314	178.4	205.7	204.5	197.4
391	421272	5.625	207.0	2.316	178.3	205.6	204.4	197.3
590	436185	5.640	206.2	2.314	177.1	205.0	203.7	196.3
160	495397	5.695	207.0	2.316	172.9	202.7	201.4	193.0
626	496355	5.696	205.6	2.313	172.9	202.7	201.4	192.9
747	544532	5.736	204.0	2.310	169.8	201.0	199.7	190.5
169	588371	5.770	207.0	2.316	167.3	199.7	198.4	188.5
627	598609	5.777	205.6	2.313	166.7	199.4	198.1	188.0
589	697446	5.844	205.8	2.314	161.7	196.7	195.4	184.0
591	732874	5.865	206.2	2.314	160.1	195.9	194.5	182.7
436	1137595	6.056	206.5	2.315	145.6	188.5	187.0	171.2
R=0.5								
274	1	0.000	680.4	2.833	625.8	640.2	717.5	581.5
283	1	0.000	649.5	2.813	625.8	640.2	717.5	581.5

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
296	1	0.000	489.1	2.689	625.8	640.2	717.5	581.5
306	1	0.000	673.1	2.828	625.8	640.2	717.5	581.5
329	1	0.000	542.6	2.734	625.8	640.2	717.5	581.5
349	1	0.000	558.5	2.747	625.8	640.2	717.5	581.5
383	1	0.000	652.4	2.815	625.8	640.2	717.5	581.5
410	1	0.000	638.3	2.805	625.8	640.2	717.5	581.5
430	1	0.000	598.9	2.777	625.8	640.2	717.5	581.5
474	1	0.000	629.5	2.799	625.8	640.2	717.5	581.5
479	1	0.000	657.4	2.818	625.8	640.2	717.5	581.5
635	1	0.000	670.1	2.826	625.8	640.2	717.5	581.5
646	1	0.000	569.3	2.755	625.8	640.2	717.5	581.5
652	1	0.000	619.3	2.792	625.8	640.2	717.5	581.5
653	1	0.000	676.4	2.830	625.8	640.2	717.5	581.5
655	1	0.000	688.8	2.838	625.8	640.2	717.5	581.5
666	1	0.000	670.9	2.827	625.8	640.2	717.5	581.5
671	1	0.000	687.3	2.837	625.8	640.2	717.5	581.5
739	1	0.000	644.3	2.809	625.8	640.2	717.5	581.5
726a	1	0.000	647.8	2.811	625.8	640.2	717.5	581.5
785	400	2.602	407.9	2.611	450.0	422.3	444.2	430.4
648	438	2.641	409.6	2.612	447.3	419.6	440.9	428.1
486	1119	3.049	412.9	2.616	419.8	393.2	409.0	404.4
650	1169	3.068	409.7	2.612	418.5	392.0	407.6	403.3
672	1400	3.146	325.4	2.512	413.2	387.1	401.7	398.8
718	1412	3.150	410.0	2.613	412.9	386.9	401.5	398.6
651	1475	3.169	408.2	2.611	411.7	385.7	400.1	397.5
571	1652	3.218	411.9	2.615	408.3	382.7	396.4	394.6
408	2290	3.360	412.9	2.616	398.7	374.1	386.2	386.4
431	2469	3.393	412.6	2.616	396.5	372.2	383.9	384.5
649	2507	3.399	410.2	2.613	396.1	371.8	383.4	384.1
572	2513	3.400	411.4	2.614	396.0	371.7	383.4	384.0
573	2519	3.401	411.4	2.614	395.9	371.6	383.3	384.0
647	2609	3.416	408.6	2.611	394.9	370.7	382.2	383.1
576	2755	3.440	411.9	2.615	393.3	369.3	380.5	381.7
717	2886	3.460	410.6	2.613	392.0	368.2	379.1	380.5
417	4100	3.613	413.1	2.616	381.6	359.3	368.6	371.7
642	5801	3.764	325.7	2.513	371.5	350.7	358.5	362.9
643	6548	3.816	324.4	2.511	367.9	347.8	355.1	359.9
641	7421	3.870	325.1	2.512	364.2	344.8	351.5	356.7
558	8357	3.922	327.5	2.515	360.7	341.9	348.2	353.7
789	11812	4.072	325.5	2.513	350.6	333.8	338.7	345.0

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
556	15905	4.202	326.6	2.514	341.9	327.0	330.7	337.5
645	19568	4.292	324.2	2.511	335.8	322.3	325.3	332.2
347	20006	4.301	327.6	2.515	335.1	321.8	324.7	331.7
560	21025	4.323	326.2	2.513	333.7	320.7	323.4	330.4
719	21037	4.323	325.5	2.513	333.6	320.7	323.4	330.4
487	21452	4.331	326.7	2.514	333.1	320.3	322.9	329.9
644	24381	4.387	326.0	2.513	329.3	317.4	319.6	326.7
562	24391	4.387	326.5	2.514	329.3	317.4	319.6	326.7
559	31685	4.501	326.6	2.514	321.6	311.7	313.0	320.1
557	38319	4.583	326.1	2.513	316.0	307.6	308.2	315.3
561	48516	4.686	326.1	2.513	309.1	302.6	302.5	309.3
409	49288	4.693	326.8	2.514	308.6	302.3	302.1	308.9
416	74500	4.872	327.7	2.515	296.5	293.7	292.2	298.5
640	98521	4.994	239.9	2.380	288.3	288.1	285.8	291.5
673	100193	5.001	239.8	2.380	287.8	287.8	285.4	291.0
488	156860	5.196	241.3	2.383	274.7	278.9	275.3	279.7
721	272818	5.436	240.0	2.380	258.4	268.4	263.4	265.8
566	280171	5.447	240.7	2.382	257.6	267.9	262.8	265.1
638	460884	5.664	240.8	2.382	243.0	258.8	252.6	252.5
636	464516	5.667	243.0	2.386	242.8	258.7	252.4	252.3
722	545546	5.737	240.2	2.381	238.1	255.8	249.2	248.3
569	763276	5.883	241.0	2.382	228.2	249.9	242.6	239.8
412	829489	5.919	241.9	2.384	225.8	248.5	241.0	237.7
563	1051280	6.022	241.1	2.382	218.8	244.4	236.4	231.7
565	1119777	6.049	240.8	2.382	217.0	243.4	235.2	230.1
418	1559097	6.193	242.0	2.384	207.3	237.8	229.1	221.8
568	1749635	6.243	240.4	2.381	203.9	235.9	227.0	218.9
564	1988538	6.299	240.8	2.382	200.1	233.8	224.7	215.7
570	2470072	6.393	240.9	2.382	193.7	230.3	220.8	210.2
R=-1								
812	1	0.000	399.5	2.601	400.1	401.9	394.9	290.5
818	1	0.000	395.8	2.597	400.1	401.9	394.9	290.5
824	1	0.000	405.5	2.608	400.1	401.9	394.9	290.5
830	1	0.000	368.3	2.566	400.1	401.9	394.9	290.5
831	1	0.000	410.5	2.613	400.1	401.9	394.9	290.5
832	1	0.000	368.2	2.566	400.1	401.9	394.9	290.5
833	1	0.000	416.4	2.620	400.1	401.9	394.9	290.5
834	1	0.000	379.0	2.579	400.1	401.9	394.9	290.5
835	1	0.000	435.1	2.639	400.1	401.9	394.9	290.5
865	1	0.000	427.5	2.631	400.1	401.9	394.9	290.5

Test #	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
866	1	0.000	408.6	2.611	400.1	401.9	394.9	290.5
867	1	0.000	406.7	2.609	400.1	401.9	394.9	290.5
868	1	0.000	387.8	2.589	400.1	401.9	394.9	290.5
869	1	0.000	419.8	2.623	400.1	401.9	394.9	290.5
880	1	0.000	370.9	2.569	400.1	401.9	394.9	290.5
881	1	0.000	404.8	2.607	400.1	401.9	394.9	290.5
882	1	0.000	427.0	2.630	400.1	401.9	394.9	290.5
883	1	0.000	397.2	2.599	400.1	401.9	394.9	290.5
884	1	0.000	421.5	2.625	400.1	401.9	394.9	290.5
885	1	0.000	394.6	2.596	400.1	401.9	394.9	290.5
886	1	0.000	411.2	2.614	400.1	401.9	394.9	290.5
887	1	0.000	374.4	2.573	400.1	401.9	394.9	290.5
888	1	0.000	415.7	2.619	400.1	401.9	394.9	290.5
889	1	0.000	413.7	2.617	400.1	401.9	394.9	290.5
1044	4861	3.687	178.4	2.251	215.3	187.8	186.9	183.9
1038	5556	3.745	182.8	2.262	212.4	185.6	184.7	182.2
1050	6004	3.778	178.3	2.251	210.7	184.3	183.4	181.2
1037	11189	4.049	182.1	2.260	197.2	174.3	173.6	173.4
1048	17397	4.240	180.6	2.257	187.5	167.5	167.0	167.9
1051	57737	4.761	144.9	2.161	161.4	150.4	150.2	152.8
1045	62837	4.798	148.5	2.172	159.6	149.3	149.1	151.7
1040	74482	4.872	146.8	2.167	155.9	147.0	146.9	149.6
1039	93249	4.970	146.2	2.165	151.0	144.1	144.0	146.8
1047	93636	4.971	146.3	2.165	150.9	144.1	144.0	146.7
1042	902103	5.955	110.2	2.042	101.6	117.6	117.9	118.3
1041	1313993	6.119	110.9	2.045	93.4	113.7	114.1	113.5
1043	1814761	6.259	111.7	2.048	86.4	110.4	110.9	109.5
1046	1962727	6.293	111.3	2.046	84.7	109.7	110.1	108.5
1049	2108317	6.324	114.5	2.059	83.1	109.0	109.4	107.6
R=10								
812	1	0.000	399.5	2.601	400.2	404.7	419.8	387.4
818	1	0.000	395.8	2.597	400.2	404.7	419.8	387.4
824	1	0.000	405.5	2.608	400.2	404.7	419.8	387.4
830	1	0.000	368.3	2.566	400.2	404.7	419.8	387.4
831	1	0.000	410.5	2.613	400.2	404.7	419.8	387.4
832	1	0.000	368.2	2.566	400.2	404.7	419.8	387.4
833	1	0.000	416.4	2.620	400.2	404.7	419.8	387.4
834	1	0.000	379.0	2.579	400.2	404.7	419.8	387.4
835	1	0.000	435.1	2.639	400.2	404.7	419.8	387.4
865	1	0.000	427.5	2.631	400.2	404.7	419.8	387.4

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
866	1	0.000	408.6	2.611	400.2	404.7	419.8	387.4
867	1	0.000	406.7	2.609	400.2	404.7	419.8	387.4
868	1	0.000	387.8	2.589	400.2	404.7	419.8	387.4
869	1	0.000	419.8	2.623	400.2	404.7	419.8	387.4
880	1	0.000	370.9	2.569	400.2	404.7	419.8	387.4
881	1	0.000	404.8	2.607	400.2	404.7	419.8	387.4
882	1	0.000	427.0	2.630	400.2	404.7	419.8	387.4
883	1	0.000	397.2	2.599	400.2	404.7	419.8	387.4
884	1	0.000	421.5	2.625	400.2	404.7	419.8	387.4
885	1	0.000	394.6	2.596	400.2	404.7	419.8	387.4
886	1	0.000	411.2	2.614	400.2	404.7	419.8	387.4
887	1	0.000	374.4	2.573	400.2	404.7	419.8	387.4
888	1	0.000	415.7	2.619	400.2	404.7	419.8	387.4
889	1	0.000	413.7	2.617	400.2	404.7	419.8	387.4
923	334	2.523	335.4	2.526	318.4	309.1	314.4	312.5
927	322	2.507	333.5	2.523	318.9	309.6	314.9	313.0
929	104	2.015	325.2	2.512	334.9	326.3	333.2	327.6
920	131	2.116	323.8	2.510	331.6	322.8	329.4	324.6
924	533	2.726	322.9	2.509	311.8	302.4	307.1	306.5
922	415	2.618	322.9	2.509	315.4	306.0	311.0	309.7
928	433	2.636	322.8	2.509	314.8	305.4	310.3	309.1
925	1019	3.008	322.7	2.509	302.7	293.5	297.4	298.1
926	327	2.514	322.7	2.509	318.7	309.4	314.7	312.8
921	364	2.561	322.4	2.508	317.2	307.8	313.0	311.4
796	11608	4.065	280.5	2.448	268.5	262.1	263.4	266.7
799	5904	3.771	279.7	2.447	278.0	270.5	272.5	275.4
855	4063	3.609	277.8	2.444	283.2	275.2	277.6	280.3
856	4410	3.644	277.7	2.444	282.1	274.2	276.4	279.2
800	5123	3.709	277.3	2.443	280.0	272.3	274.4	277.3
817	15393	4.187	277.2	2.443	264.5	258.7	259.8	263.1
816	3850	3.585	277.2	2.443	284.0	275.9	278.3	280.9
858	8288	3.918	277.0	2.442	273.2	266.2	267.9	271.1
797	2463	3.391	276.8	2.442	290.3	281.7	284.6	286.7
859	10692	4.029	276.5	2.442	269.6	263.1	264.5	267.8
814	4353	3.639	276.4	2.442	282.3	274.3	276.6	279.4
798	2727	3.436	276.4	2.441	288.8	280.3	283.1	285.4
813	2469	3.392	276.0	2.441	290.2	281.6	284.5	286.7
857	1957	3.291	275.4	2.440	293.5	284.7	287.9	289.7
806	5010	3.700	259.1	2.413	280.3	272.5	274.7	277.5
805	21240	4.327	245.3	2.390	260.0	254.9	255.6	258.9

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
802	54873	4.739	243.9	2.387	246.6	243.9	243.8	246.7
823	67973	4.832	243.1	2.386	243.6	241.5	241.3	243.9
804	11738	4.070	243.1	2.386	268.3	262.0	263.3	266.6
820	36657	4.564	243.0	2.386	252.3	248.5	248.8	251.9
819	14172	4.151	242.9	2.385	265.7	259.7	260.8	264.1
803	11145	4.047	242.8	2.385	269.0	262.6	264.0	267.2
801	379064	5.579	242.6	2.385	219.4	223.0	221.5	221.8
822	9235	3.965	242.5	2.385	271.7	264.9	266.5	269.7
821	6704	3.826	241.4	2.383	276.2	268.9	270.7	273.8
863	1884110	6.275	216.5	2.335	196.8	207.0	204.5	201.1
861	933072	5.970	216.4	2.335	206.7	213.8	211.8	210.1
828	1508674	6.179	215.2	2.333	200.0	209.1	206.8	203.9
808	1680674	6.225	214.5	2.331	198.4	208.1	205.6	202.6
807	487946	5.688	211.5	2.325	215.9	220.4	218.7	218.5
827	1037244	6.016	209.9	2.322	205.2	212.8	210.6	208.8
811	1464645	6.166	209.1	2.320	200.4	209.4	207.1	204.3
829	842537	5.926	208.5	2.319	208.2	214.9	212.8	211.5
825	1505733	6.178	208.2	2.318	200.0	209.1	206.8	204.0
809	1859843	6.269	208.1	2.318	197.0	207.1	204.6	201.3
810	1747111	6.242	208.1	2.318	197.9	207.7	205.2	202.1
860	2021912	6.306	208.0	2.318	195.8	206.3	203.8	200.2
862	205084	5.312	207.9	2.318	228.1	229.4	228.3	229.7
826	1980344	6.297	207.9	2.318	196.1	206.5	204.0	200.4
864	235297	5.372	207.5	2.317	226.1	228.0	226.8	227.9
R=2								
812	1	0.000	399.5	2.601	402.5	402.4	465.0	404.9
818	1	0.000	395.8	2.597	402.5	402.4	465.0	404.9
824	1	0.000	405.5	2.608	402.5	402.4	465.0	404.9
830	1	0.000	368.3	2.566	402.5	402.4	465.0	404.9
831	1	0.000	410.5	2.613	402.5	402.4	465.0	404.9
832	1	0.000	368.2	2.566	402.5	402.4	465.0	404.9
833	1	0.000	416.4	2.620	402.5	402.4	465.0	404.9
834	1	0.000	379.0	2.579	402.5	402.4	465.0	404.9
835	1	0.000	435.1	2.639	402.5	402.4	465.0	404.9
865	1	0.000	427.5	2.631	402.5	402.4	465.0	404.9
866	1	0.000	408.6	2.611	402.5	402.4	465.0	404.9
867	1	0.000	406.7	2.609	402.5	402.4	465.0	404.9
868	1	0.000	387.8	2.589	402.5	402.4	465.0	404.9
869	1	0.000	419.8	2.623	402.5	402.4	465.0	404.9
880	1	0.000	370.9	2.569	402.5	402.4	465.0	404.9

Test No.	Total Cycles	Log Cycles	MPa, Max Stress	Log Stress	Exponent All Data	Power All Data	Power -Static	Exponent -Static
881	1	0.000	404.8	2.607	402.5	402.4	465.0	404.9
882	1	0.000	427.0	2.630	402.5	402.4	465.0	404.9
883	1	0.000	397.2	2.599	402.5	402.4	465.0	404.9
884	1	0.000	421.5	2.625	402.5	402.4	465.0	404.9
885	1	0.000	394.6	2.596	402.5	402.4	465.0	404.9
886	1	0.000	411.2	2.614	402.5	402.4	465.0	404.9
887	1	0.000	374.4	2.573	402.5	402.4	465.0	404.9
888	1	0.000	415.7	2.619	402.5	402.4	465.0	404.9
889	1	0.000	413.7	2.617	402.5	402.4	465.0	404.9
897	46304	4.666	280.6	2.448	285.3	280.7	286.9	285.7
899	48990	4.690	273.8	2.438	284.7	280.1	286.2	285.1
893	62258	4.794	274.7	2.439	282.1	277.9	283.1	282.4
892	130733	5.116	275.9	2.441	274.0	271.1	273.8	274.2
894	158396	5.200	279.3	2.446	271.9	269.3	271.5	272.0
896	162400	5.211	280.9	2.449	271.6	269.1	271.2	271.8
898	192595	5.285	275.9	2.441	269.8	267.6	269.1	269.9
895	1442932	6.159	273.4	2.437	247.8	250.1	245.8	247.5
909	2738468	6.438	242.4	2.384	240.8	244.8	238.8	240.4
919	4013900	6.604	208.2	2.318	236.6	241.7	234.8	236.2

APPENDIX C

MULTI-BLOCK FATIGUE TEST SUMMARY

Description of Table Headings for Appendix C

1) Test No. - Coupon identification number.

2) Actual Miner's number - calculated from the cycles conducted based upon average number of cycles to failure at the individual load levels.

3) Fraction Hi - fractional amount of number of high amplitude block cycles to the total number of cycles endured.

4) NRSD exponent all data - a nonlinear residual strength degradation equation was used in conjunction with an exponential fit of the fatigue data including all tests (as opposed to excluding the static tests).

5) LRSD exponent all data - a linear residual strength degradation equation was used in conjunction with an exponential fit of the fatigue data including all tests (as opposed to excluding the static tests).

6) NRSD exponent -static - a nonlinear residual strength degradation equation was used in conjunction with an exponential fit of the fatigue data, excluding the static tests.

7) LRSD exponent -static - a linear residual strength degradation equation was used in conjunction with an exponential fit of the fatigue data, excluding the static tests.

8) NRSD power all data - a nonlinear residual strength degradation equation was used in conjunction with an power fit of the fatigue data including all tests (as opposed to excluding the static tests).

9) LRSD power all data - a linear residual strength degradation equation was used in conjunction with an power fit of the fatigue data including all tests (as opposed to excluding the static tests).

10) NRSD power -static - a nonlinear residual strength degradation equation was used in conjunction with an power fit of the fatigue data, excluding the static tests.

11) LRSD power -static - a linear residual strength degradation equation was used in conjunction with an power fit of the fatigue data, excluding the static tests.

Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
414 / 328 MPa, R = 0.1										
		0.505					0.871			
		0.102					0.579			
		0.052					0.487			
		0.011					0.531			
		0.005					0.987			
		0.005					1.053			
		0.005					1.053			
		0.005					1.053			
		0.005					1.053			
		0.005					1.053			
		0.514						0.985		
		0.101						0.921		
		0.054						0.828		
		0.010						1.043		
		0.005						0.987		
		0.005						1.021		
		0.005						1.021		
		0.005						1.021		
		0.005						1.021		
		0.005						1.021		
		0.510							0.865	
		0.102							0.526	
		0.052							0.447	
		0.011							0.498	
		0.005							0.929	
		0.004							1.047	
		0.004							1.047	
		0.004							1.047	
		0.004							1.047	
		0.004							1.047	
		0.502								0.978
		0.108								0.876
		0.051								0.888
		0.010								0.990
		0.005								0.929
		0.004								1.019

		0.004								1.019
		0.004								1.019
		0.004								1.019
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
		0.004								1.019
		0.509	0.836							
		0.101	0.458							
		0.051	0.362							
		0.010	0.485							
		0.005	0.456							
		0.002	1.024							
		0.002	1.024							
		0.002	1.024							
		0.002	1.024							
		0.002	1.024							
		0.509		0.974						
		0.101		0.863						
		0.051		0.796						
		0.010		0.726						
		0.005		0.909						
		0.002		1.010						
		0.002		1.010						
		0.002		1.010						
		0.002		1.010						
		0.002		1.010						
		0.512			0.824					
		0.112			0.411					
		0.052			0.323					
		0.011			0.426					
		0.005			0.750					
		0.003			1.083					
		0.003			1.083					
		0.003			1.083					
		0.003			1.083					
		0.003			1.083					
		0.526				0.979				
		0.101				0.879				
		0.051				0.793				
		0.010				0.842				
		0.005				0.750				

		0.003				1.040				
		0.003				1.040				
		0.003				1.040				
		0.003				1.040				
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
		0.003				1.040				
256	0.122	0.512								
257	0.148	0.016								
258	0.083	0.121								
259	0.168	0.115								
260	0.318	0.016								
310	0.565	0.502								
311	0.982	0.102								
312	0.141	0.019								
579	0.244	1.000								
577	0.959	1.000								
297	1.051	1.000								
621	1.664	1.000								
620	0.610	1.000								
578	0.793	1.000								
606	0.929	1.000								
129	0.969	1.000								
130	0.264	1.000								
148	0.505	1.000								
172	0.525	1.000								
623	0.549	1.000								
624	1.054	1.000								
605	0.546	1.000								
433	2.654	1.000								
580	2.566	1.000								
308	1.132	1.000								
282	0.308	1.000								
313	0.288	1.000								
622	1.454	1.000								
298	0.983	1.000								
213	1.207	0.000								
161	1.343	0.000								
171	0.699	0.000								
139	1.280	0.000								
168	0.933	0.000								

582	0.302	0.000								
434	1.702	0.000								
583	1.521	0.000								
214	1.064	0.000								
140	0.844	0.000								
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
617	0.777	0.000								
619	0.988	0.000								
608	0.946	0.000								
607	0.729	0.000								
616	0.686	0.000								
206	0.439	0.000								
581	0.544	0.000								
376	1.777	0.000								
554	0.693	0.000								
584	0.310	0.000								
321	0.530	0.000								
325	1.061	0.000								
618	3.515	0.000								
414 / 241 MPa, R = 0.1										
		0.509					0.990			
		0.101					0.898			
		0.055					0.827			
		0.010					0.512			
		0.005					0.388			
		0.001					0.191			
		0.001					0.301			
		0.000					1.066			
		0.000					1.066			
		0.000					1.066			
		0.513						1.005		
		0.103						0.995		
		0.050						0.987		
		0.011						0.915		
		0.005						0.864		
		0.001						0.741		
		0.001						0.646		
		0.000						1.033		
		0.000						1.033		
		0.000						1.033		

		0.503							0.990	
		0.103							0.891	
		0.054							0.798	
		0.010							0.464	
		0.005							0.357	
		0.001							0.185	
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
		0.001							0.299	
		0.000							1.058	
		0.000							1.058	
		0.000							1.058	
		0.507								1.003
		0.106								0.990
		0.052								0.980
		0.011								0.904
		0.005								0.834
		0.001								0.721
		0.001								0.630
		0.000								1.029
		0.000								1.029
		0.000								1.029
		0.502	0.957							
		0.103	0.707							
		0.050	0.550							
		0.010	0.232							
		0.005	0.180							
		0.001	0.172							
		0.001	0.310							
		0.000	1.029							
		0.000	1.029							
		0.000	1.029							
		0.504		0.998						
		0.102		0.966						
		0.051		0.935						
		0.010		0.784						
		0.005		0.711						
		0.001		0.680						
		0.001		0.617						
		0.000		1.015						
		0.000		1.015						

		0.000		1.015						
		0.505			0.970					
		0.102			0.787					
		0.056			0.658					
		0.010			0.326					
		0.005			0.242					
		0.001			0.211					
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
		0.001			0.318					
		0.000			1.092					
		0.000			1.092					
		0.000			1.092					
		0.515				1.008				
		0.103				0.988				
		0.050				0.980				
		0.010				0.882				
		0.005				0.823				
		0.001				0.614				
		0.001				0.626				
		0.000				1.056				
		0.000				1.056				
		0.000				1.056				
		1.000								
		0.500								
		0.100								
		0.050								
		0.010								
		0.005								
		0.001								
		0.001								
		0.000								
		0.000								
579	0.959	1.000								
577	1.051	1.000								
297	1.664	1.000								
621	0.610	1.000								
620	0.793	1.000								
578	0.929	1.000								
606	0.969	1.000								
129	0.264	1.000								

130	0.505	1.000								
148	0.525	1.000								
172	0.549	1.000								
623	1.054	1.000								
624	0.546	1.000								
605	2.654	1.000								
433	2.566	1.000								
580	1.132	1.000								

Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
308	0.308	1.000								
282	0.288	1.000								
313	1.454	1.000								
622	0.983	1.000								
298	1.207	1.000								
142	0.308	0.001								
136	0.162	0.001								
134	0.396	0.004								
132	0.369	0.010								
143	0.297	0.012								
144	0.504	0.031								
133	0.169	0.038								
145	0.369	0.083								
135	0.933	0.085								
146	1.125	0.505								
137	0.511	0.520								
149	0.725	0.163								
150	0.777	0.165								
215	0.145	0.002								
275	1.183	0.083								
300	0.486	0.001								
304	1.263	0.082								
307	0.169	0.109								
302	0.626	0.000								
326	1.203	0.000								
284	1.259	0.000								
138	1.648	0.000								
131	1.624	0.000								
323	0.194	0.000								
174	0.435	0.000								
147	0.367	0.000								

205	0.180	0.000								
633	0.500	0.000								
610	0.501	0.000								
630	0.663	0.000								
609	0.676	0.000								
632	0.432	0.000								
435	2.086	0.000								
588	2.152	0.000								
634	1.881	0.000								
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
585	2.140	0.000								
586	1.029	0.000								
587	0.403	0.000								
328 / 241 MPa, R = 0.1										
		0.501					0.963			
		0.101					0.775			
		0.050					0.661			
		0.010					0.465			
		0.005					0.426			
		0.001					0.459			
		0.001					0.450			
		0.000					1.003			
		0.000					1.003			
		0.000					1.003			
		0.501						0.993		
		0.100						0.950		
		0.050						0.918		
		0.010						0.835		
		0.005						0.821		
		0.001						0.803		
		0.001						0.900		
		0.000						1.001		
		0.000						1.001		
		0.000						1.001		
		0.500							0.960	
		0.100							0.763	
		0.050							0.647	
		0.010							0.467	
		0.005							0.431	
		0.001							0.472	

		0.001							0.463	
		0.000							1.003	
		0.000							1.003	
		0.000							1.003	
		0.500								0.993
		0.100								0.947
		0.050								0.912
		0.010								0.826
		0.005								0.808
		0.001								0.825
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
		0.001								0.926
		0.000								1.001
		0.000								1.001
		0.000								1.001
		0.500	0.897							
		0.100	0.591							
		0.050	0.493							
		0.010	0.394							
		0.005	0.384							
		0.001	0.420							
		0.001	0.555							
		0.000	1.001							
		0.000	1.001							
		0.000	1.001							
		0.500		0.981						
		0.100		0.894						
		0.050		0.849						
		0.010		0.788						
		0.005		0.770						
		0.001		0.839						
		0.001		0.833						
		0.000		1.001						
		0.000		1.001						
		0.000		1.001						
		0.501			0.918					
		0.100			0.610					
		0.050			0.482					
		0.010			0.318					
		0.005			0.294					

		0.001			0.330					
		0.001			0.434					
		0.000			1.002					
		0.000			1.002					
		0.000			1.002					
		0.500				0.987				
		0.100				0.913				
		0.050				0.860				
		0.010				0.760				
		0.005				0.735				
		0.001				0.769				

Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
		0.001				0.867				
		0.000				1.001				
		0.000				1.001				
		0.000				1.001				
		0.500								
		0.100								
		0.050								
		0.010								
		0.005								
		0.001								
		0.001								
		0.000								
		0.000								
		0.000								
		1.000								
		0.500								
		0.100								
		0.050								
		0.010								
		0.005								
		0.001								
		0.001								
		0.000								
177	1.009	0.010								
178	0.296	0.010								
194	0.204	0.011								
195	0.641	0.003								
196	0.247	0.002								

198	0.209	0.020								
199	0.112	0.092								
200	0.251	0.501								
201	0.083	0.021								
202	0.146	0.011								
203	0.222	0.003								
204	0.441	0.004								
209	0.105	0.501								
210	0.332	0.501								
217	0.246	0.004								
279	1.024	0.002								
280	0.126	0.010								
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
350	1.380	0.500								
351	0.649	0.100								
213	1.343	1.000								
161	0.699	1.000								
171	1.280	1.000								
139	0.933	1.000								
168	0.302	1.000								
582	1.702	1.000								
434	1.521	1.000								
583	1.064	1.000								
214	0.844	1.000								
140	0.777	1.000								
617	0.988	1.000								
619	0.946	1.000								
608	0.729	1.000								
607	0.686	1.000								
616	0.439	1.000								
206	0.544	1.000								
581	1.777	1.000								
376	0.693	1.000								
554	0.310	1.000								
584	0.530	1.000								
321	1.061	1.000								
325	3.515	1.000								
618	0.312	1.000								
302	0.626	0.000								
326	1.203	0.000								

284	1.259	0.000								
138	1.648	0.000								
131	1.624	0.000								
323	0.194	0.000								
174	0.435	0.000								
147	0.367	0.000								
205	0.180	0.000								
633	0.500	0.000								
610	0.501	0.000								
630	0.663	0.000								
609	0.676	0.000								
632	0.432	0.000								
435	2.086	0.000								
Test No.	actual Miner's number	Fraction Hi	NRSD exponent all data	LRSD exponent all data	NRSD exponent -static	LRSD exponent -static	NRSD power all data	LRSD power all data	NRSD power -static	LRSD power -static
588	2.152	0.000								
634	1.881	0.000								
585	2.140	0.000								
586	1.029	0.000								
587	0.403	0.000								

APPENDIX D

WISPERX FATIGUE TEST SUMMARY

Description of Table Headings for Appendix D

1) Test No. - test identification number

2) Max Load, pounds - the maximum load, in pounds, encountered during the test.

3) Max Stress, MPa - the maximum stress, in MPa, encountered during the test, determined from Max load and test section dimensions.

4) Cycles - number of cycles encountered (rounded to the nearest greater integer in the static test case).

5) Exponent Regression - the stress to failure as determined from an exponential regression of the data.

6) LRSD Exponent Predict - the stress to failure as predicted using a linear residual strength degradation equation and an exponential fit of the fatigue data (fatigue data being the single load level test results).

7) NRSD Exponent Predict - the stress to failure as predicted using a nonlinear residual strength degradation equation and an exponential fit of the fatigue data (fatigue data being the single load level test results).

8) Miner's Prediction - the stress to failure as predicted by employing Miner's rule or sum (based upon the average cycles to failure at the single load level tests).

9) NRSD Power Predict - the stress to failure as predicted using a nonlinear residual strength degradation equation and a power fit of the fatigue data (fatigue data being the single load level test results).

10) LRSD Power Predict - the stress to failure as predicted using a linear residual strength degradation equation and a power fit of the fatigue data (fatigue data being the single load level test results).

Mod2 WisperX Spectrum, R=0.1									
Test No.	Max Load, pounds	Max Stress, MPa	Cycles	Exponent Regression	LRSD Exponent Predict	NRSD Exponent Predict	Miner's Prediction	NRSD Power Predict	LRSD Power Predict
615	5544	622.0	1	641.4					
635	5901	670.1	1	641.4					
646	4953	569.3	1	641.4					
652	4285	619.3	1	641.4					
653	5624	676.4	1	641.4					
655	5879	688.8	1	641.4					
666	5726	670.9	1	641.4					
739	5734	696.9	1	641.4					
726	5765	647.8	1	641.4					
671	5633	687.3	1	641.4					
971	2875	340.9	1276	430.2					
972	2960	343.6	2325	412.4					
973	2889	344.7	2448	410.9					
976	3115	402.9	2806	406.9					
974	3352	406.9	3130	403.6					
979	3669	402.3	3203	403.0					
978	3387	406.2	3233	402.7					
970	2914	402.9	3844	397.6					
975	3081	403.2	4044	396.1					
977	2716	405.6	5722	385.8					
1004	3026	339.5	6048	384.2					
1005	2613	341.2	13058	361.4					
1000	2945	335.4	14371	358.6					
1002	2593	340.9	18334	351.4					
1006	2698	343.2	24196	343.2					
1003	2934	340.2	24906	342.4					
1001	2810	335.5	26045	341.0					
986	2524	296.9	68426	312.5					
989	2458	297.5	80980	307.5					
983	2669	301.6	86293	305.7					
988	2543	297.0	144430	290.4					
981	2475	298.0	155850	288.2					
980	2233	297.9	167885	286.0					
985	2299	298.0	169839	285.7					
982	2462	297.2	195616	281.5					
990	2338	254.1	195751	281.5					
987	2319	297.4	231019	276.6					

999	2227	256.1	248429	274.4					
Test No.	Max Load, pounds	Max Stress, MPa	Cycles	Exponent Regression	LRSD Exponent Predict	NRSD Exponent Predict	Miner's Prediction	NRSD Power Predict	LRSD Power Predict
984	2270	296.8	298800	269.0					
995	2222	254.6	312744	267.6					
996	2164	259.1	432307	258.1					
991	2202	255.0	598438	248.5					
998	2175	255.6	680774	244.6					
992	1878	255.9	876955	237.2					
997	1979	256.7	912240	236.0					
993	1878	253.1	1231928	227.1					
1016	1550	189.7	12289518	159.2					
1007	1550	185.6	14130978	155.0					
			12983		414				
			92466		327.75				
			836664		241.5				
			1952961		207				
			2649			414			
			41142			327.75			
			503058			241.5			
			1298580			207			
			13409				414		
			117716				327.75		
			984459				241.5		
			2284731				207		
			2649					414	
			41142					327.75	
			1863144					241.5	
			1E+07					207	
			1497						414
	644		28311						327.75
	31		1118946						241.5
	1		6777417						207