SPECTRUM FATIGUE LIFETIME AND RESIDUAL STRENGTH FOR FIBERGLASS LAMINATES IN TENSION

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ABSTRACT

This paper addresses the effects of spectrum loading on lifetime and residual strength. Over 900 tests have been run on a typical fiberglass laminate configuration under a variety of load sequences. Repeated block loading at two or more load levels as well as a modified standard spectrum 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 10-20% 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 the better fit of the two. Direct tests of residual strength at various fractions of the lifetime are consistent with the residual strength damage models for several cases. Load sequencing effects are not found to be significant. 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 adequate correlation with the experimental results.

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.

INTRODUCTION

An investigation of the relationship between spectrum loading and fatigue lifetimes of a typical wind turbine blade fiberglass material has been undertaken for the development of refined design tools. Present design tools for estimating lifetimes of fiberglass materials produce results that may be significantly non-conservative for some loads spectra. These tools or prediction models range from the simple Miner's sum and the various deviations to more complicated ones based upon residual strength.[1-9] Many require testing of the materials to establish "fitting" parameters to obtain the best performance of the model. The objective of this study is to identify cumulative damage laws which provide improved accuracy in predicting lifetime under a variety of loads spectra for wind turbine blade materials..

This program of spectrum loading for fatigue of fiberglass materials was conducted in a logical progression from simple to complicated spectra; that is, from constant amplitude loading, to multi-amplitude loading, to a modified standard spectrum. Small dog-bone coupons were manufactured, tested and favorably compared to standard tensile test coupons. Baseline data for the development of stress-cycle (S-N) trends was obtained by constant amplitude fatigue of coupons by using computer controlled hydraulic testing equipment. Results of this preliminary testing are consistent with earlier work.[10]

Tests were then run using repeated blocks at two stress levels. Initially this two-block testing was such that the first block contained ten cycles of the higher stress load, followed by a varying number of cycles at a lower stress level, repeated until failure. Two-block testing by some investigators has been limited to the application of a fixed number of cycles of the first stress level, followed by an undetermined number of cycles at a second level, until failure. This reportedly results in either Miner's sums greater than unity for high stress levels followed by low stress levels or Miner's sums less than unity for low stress levels followed by high stress levels.[11] The present work used the more general case of repeated application of two-blocks until failure, and also explored load sequencing effects.

Testing of multi-block spectra was then performed with blocks of three and six stress levels. Finally, coupons were subjected to a modified WISPERX[12,13] spectrum which has been reported to produce Miner's sums less than unity.

NOMENCLATURE AND DEFINITIONS

The linear damage accumulation rule of Miner's sum is frequently applied to fatigue test results and is here defined as:

$$D = \sum_i \frac{n_i}{N_i} \qquad (1)$$

where D is a quantified damage accumulation parameter, n_i is the number of cycles experienced at a $ó_i$ maximum stress level and N_i is the number of constant amplitude cycles to failure at the maximum stress level $ó_i$. Typically, failure is taken to occur when D reaches unity, as originally proposed by M. A. Miner[14].

The cyclic loading of a specimen is frequently reported as a maximum stress and an R-value. The R-value is the ratio of the minimum to maximum stress. Several common constant amplitude sinusoidal loading waveforms are shown in Fig. 1, along with their R-values.

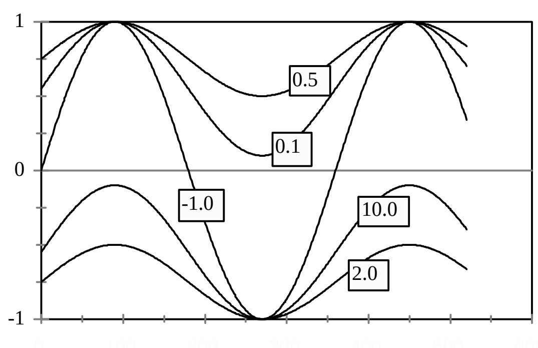

Figure 1. Typical Waveforms With Different R-Values

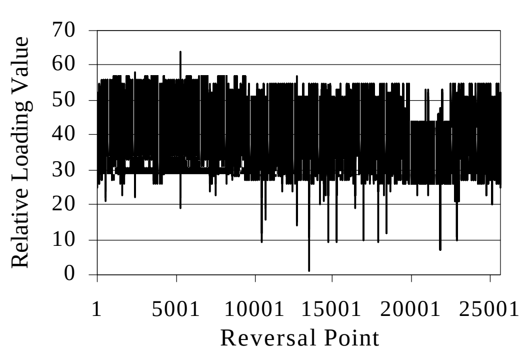

Figure 2. WISPERX Spectrum

WISPERX[12,13] is a European standardized loading spectrum which has been used for analysis of fatigue of wind turbine components. It is provided as a sequence of numbers ranging from 1 to 64, with 25 as a zero value. WISPERX contains 25,663 loading reversal points for 12,831 cycles. An overall visual presentation of the WISPERX spectra is shown in Fig. 2.

In this study, WISPERX was modified to a spectrum of constant R-value by adjusting the valley reversal point after each peak reversal point. This was done for R-values of 0.1 and 0.5, as demonstrated in Fig. 3 for a small portion of the WISPERX spectrum.

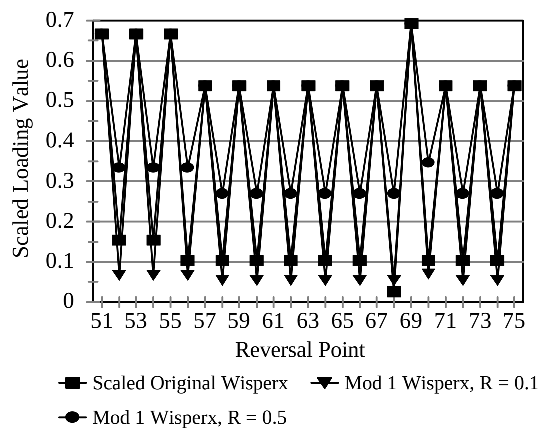

Figure 3. Modified WISPERX Spectrum Example

The WISPERX spectrum was scaled for use with testing machinery control software. The results are shown in Fig. 4.

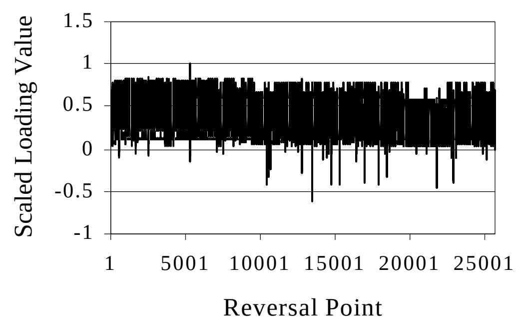

Figure 4. Scaled WISPERX Spectrum

The first modification only included cycles that were tensile-tensile. The results of this modification were called the Mod 1 spectrum and are displayed in Fig. 5. A second modification, that included all peak reversal points, was created. The resultant spectrum, Mod 2 spectrum, is displayed in Fig. 6. The main thrust of the modification was to create spectra that were of a constant R-value, thereby aiding in the application of the baseline constant amplitude fatigue data for lifetime predictions. Comparison of the Mod 1 and Mod 2 spectra allowed an investigation into the damage contribution of essentially one major event per pass through the spectrum.

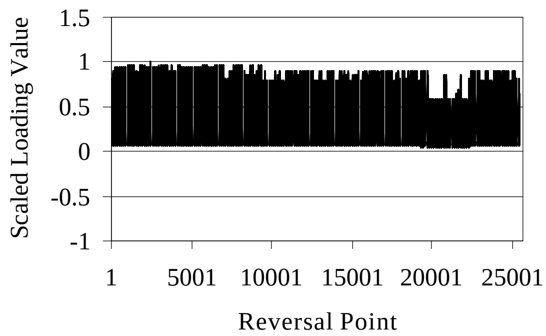

Figure 5. Mod 1 Spectrum for R = 0.1

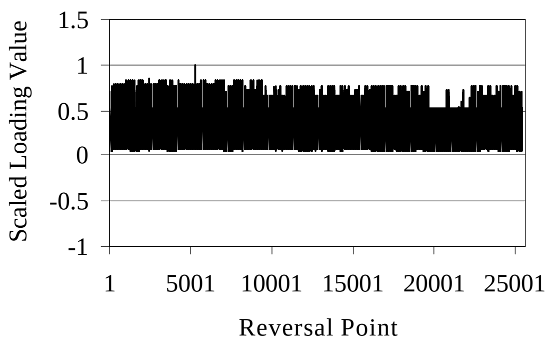

Figure 6. Mod 2 Spectrum for R = 0.1

EXPERIMENTAL METHODS

Material and Test Specimens

The material, termed DD16 in the database[10], was comprised of Owens Corning D155 and DB120 fabrics in a $[90/0/\pm45/0]_S$ lay-up. Plates of this material were fabricated by a resin transfer molding, RTM, process with Interplastics Corp. CoRezyn 63-AX-051 orthopolyester matrix to an average fiber volume fraction of 0.36. Details can be found in the current version of the DOE/MSU Fatigue Database and Ref. 10.

Tensile-tensile specimen blanks were rectangularly shaped, 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 and master pattern. Fiberglass tab material was attached to provide distribution of testing machine gripping forces. The minimum width of the dog-bone gage section was typically 9.5 mm.

Testing Equipment

An Instron 8872 hydraulic testing machine, with an Instron 8800 controller was used to subject the specimen to the spectrum loads. Instron WaveRunner © and RANDOM © * software packages were used to develop and apply the loading spectra. Secondary measurement and recording of the actual loading waveforms were favorably compared to that available from the Instron equipment.

Testing was performed at 8 or 10 Hz, with forced air surface cooling of the specimen to preclude thermal effects.

TESTING AND RESULTS

Constant Amplitude Testing

The fatigue results of the single amplitude testing are summarized in the stress-cycle (S-N) diagram, Fig. 7, for R = 0.1 and R = 0.5.

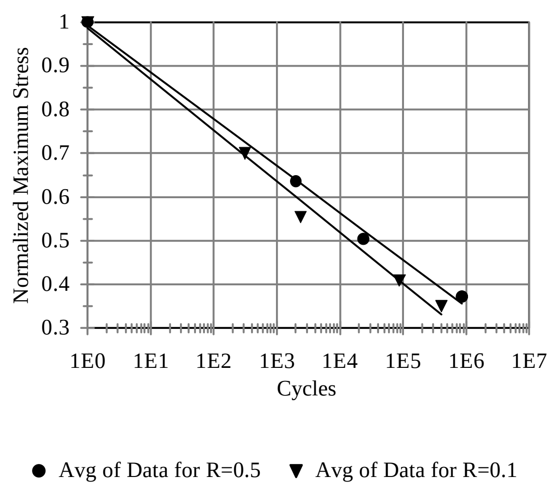

Figure 7. Constant Amplitude S-N Fatigue Data

The slopes for the two tensile-tensile S-N lines are -0.108 and -0.119 for R = 0.5 and 0.1 respectively. Over 175 tests are represented by the information in Fig. 7. Both regression lines have correlation coefficients better than 0.98.

The generic equation[15] for the two lines in Fig. 7 is:

$$\frac{s}{s_0} = 1 + b * \log(N) \qquad (2)$$

* WaveRunner and RANDOM are Instron Corporation waveform development and control programs.

Where ó = maximum applied stress, MPa
$ó_0$ = static strength, MPa
N = number of cycles to failure
b = slope or reduction in maximum applied stress for each decade increase in cycles.

For R = 0.1, $ó_0$ = 578.7 MPa, b = -0.119
R = 0.5, $ó_0$ = 642.2 MPa, b = -0.108

The average data shown in Fig. 7 reflects the average cycles to failure at a given load level. The different $ó_0$ values at R = 0.1 and R = 0.5 reflect different material batches.

Two-block Testing

Two-block testing was performed with both the Instron WaveRunner and RANDOM control programs. This testing was used to study both the effect of a simple spectrum on fatigue and the effect of the sequencing of cycles within the spectrum.

Testing of the sequence effect involved applying ten cycles of high stress level within 1000 cycles of a lower stress level. Three cases were chosen: 1) one high amplitude cycle followed by 100 low; 2) ten high amplitude cycles followed by 1000 low; and 3) ten high amplitude cycles randomly interspersed within 1000 low. These spectra are shown, respectively, top to bottom in Fig. 8.

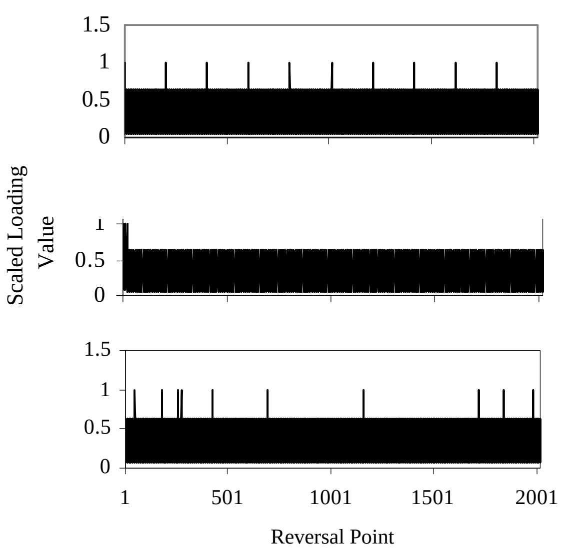

Figure 8. Two-Block Sequencing (sequences shown repeated to failure)

The results of these tests are displayed on the occurrence graph, Fig. 9. The single amplitude results are also shown for comparison. Note the center three sets of data representing the two-block fatigue tests at three different sequences. Statistically, no differences could be found among the results. The 120 tests, 82 two-block and 38 constant amplitude, represented in Fig. 9, were all performed for R = 0.1. The high stress level was 325 MPa and the low stress level was 207 MPa.

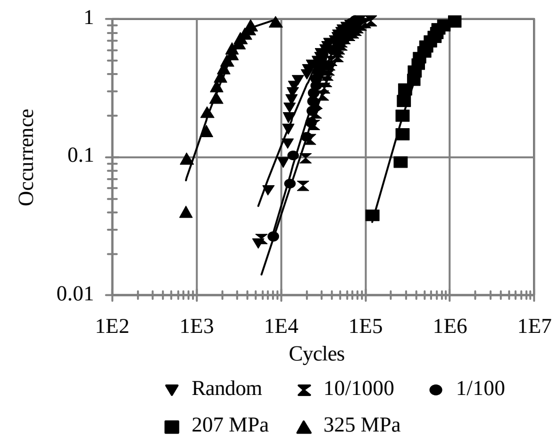

Figure 9. Sequence Effects on Two-block Repeated Spectra, R = 0.1

Consider Fig. 10 depicting these same 82 two-block tests now as a function of Miner's sum. Only four of the 82 tests achieved Miner's sums of greater than one. It is evident that the sum tends to less than unity for two-block loading, causing the Miner's sum rule to be non-conservative.

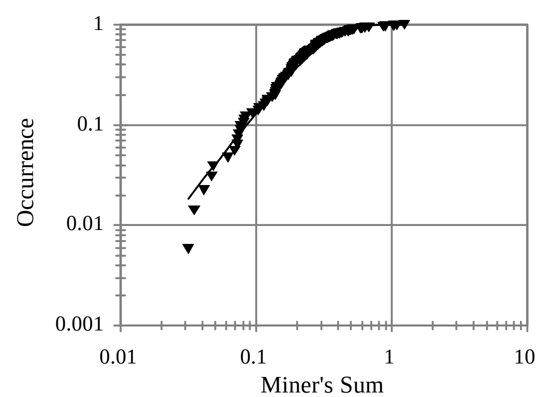

Figure 10. Combined Two-block Miner's Sum Results, R = 0.1

Additional two-block results were obtained by varying the fraction of high amplitude cycles. A representation of Miner's sum as a function of the fraction of the higher stress cycles shows a trend of unity for fractions of zero and 1, with sums less than unity for fractions in between. A typical graph of these results is shown in Fig. 11.

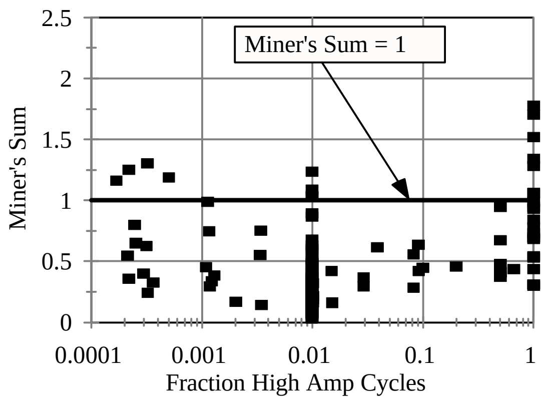

Figure 11. Typical Two-block Miner's Sum for High and Low Blocks of 325 and 207 MPa, R = 0.1

The tests summarized in Fig. 11 are those of repeated two-block loading with the higher amplitude block of ten cycles run with a maximum stress of 325 MPa and the lower amplitude block of preselected number of cycles at 207 MPa. Several other cases have also been run at different stresses with results which are consistent with Fig. 11.

Multi-Block Testing

Testing for spectra with three and six stress levels has also revealed Miner's sums that are consistently less than unity. The three block testing program was constructed as a mix of ten cycles of 414 MPa, ten cycles of 325 MPa, and 100 cycles of 235 MPa in various sequences.

The six block testing consisted of four stress levels arranged into six blocks as:

Table I. 6-Block Sequence[7]

# Cycles	% of Maximum Stress
1000	30
1000	50
400	75
10	100
400	75
1000	50

The three and six block testing were all performed with R = 0.1; results are presented in Table II for the three-block and Table III for the six-block. Note, all Miner's sums are less than unity.

Table II. Three-Block Test Results
R = 0.1

Test No.	Sequence Cycles	Load	Actual Cycles	Miner's Sum Actual	Miner's Sum Linear Prediction	Miner's Sum 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 III. Six-Block Test Results
R = 0.1

Test No.	Sequence Cycles	Load	Actual Cycles	Miner's Sum Actual	Miner's Sum Linear Prediction	Miner's Sum 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			

Modified WISPERX Testing

The WISPERX spectrum was modified to maintain a constant R value throughout as described earlier. This was done to allow direct use of the constant amplitude baseline data for R values of 0.1 and 0.5, in the model predictions. Two versions, Mod 1 and Mod 2 were described earlier.

The results for the Mod 1 and 2 spectra testing are summarized in Figs. 12 and 13 respectively. The trend of longer lifetimes for the R=0.5 loading are also typical for constant amplitude testing (Fig. 7). The spectra loads were adjusted relative to the maximum stress in the spectrum following Figs. 4-6, with only the maximum stress plotted in Figs. 12 and 13.

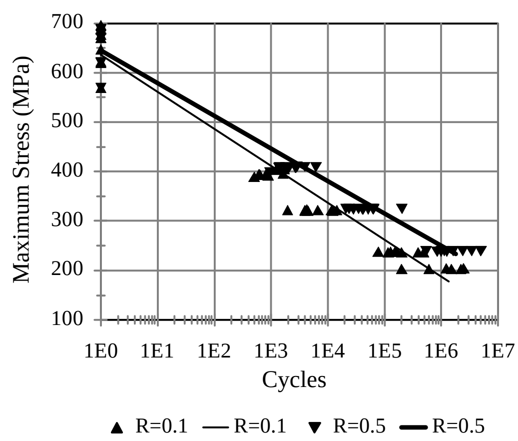

Figure 12. Mod 1 Fatigue S-N
(S is the maximum stress in the spectrum)

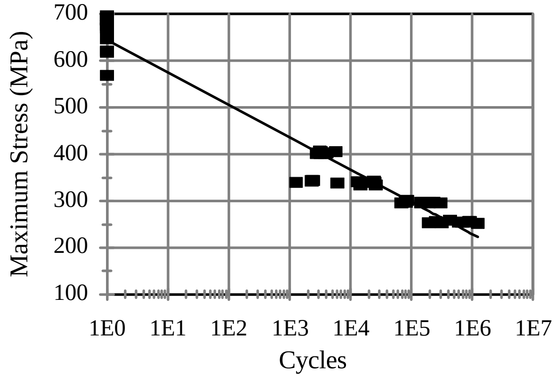

Figure 13. Mod 2 Spectra Fatigue S-N, R = 0.1
(S is the maximum stress in the spectrum)

Testing Summary

The spectrum testing program was implemented to vary the complexity of the spectra, from constant amplitude loading for base line data to multi-block spectra and finally to more random spectra. The latter used two modified WISPERX spectra, Mod 1 and 2. The method of establishing a set of blocks and then repeating these blocks until specimen failure is considered to be more representative of service loading as compared with continuing the final block to failure and not repeating the sequence.

In nearly every test, the Miner's sum at failure is less than unity. The need for improved models is evident.

LIFETIME PREDICTIONS

An accurate cumulative damage law is essential to component design under spectrum loading. The fundamental and most widely applied damage law is that established by Palmgren and Miner. Under this law, damage is considered to develop linearly as a function of the number of cycles encountered at specific load levels. As reported throughout this paper, the Miner's sum is consistently less than unity, often on the order of 0.1, for testing under spectra of more than one block.

A component or specimen is considered to have failed when it can no longer support the load intended. Tensile failure was usually a sudden separation of 0^{o} fibers, brooming out from the matrix. 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.

Residual Strength Degradation Models

Consider that the strength of a specimen may decrease linearly as the part is loaded cyclically.[9] This can readily be applied to block loading to estimate lifetimes. In Fig. 14, the strength and cycles have been normalized to the static strength and cycles to failure respectively. The maximum stress, in this case, is half of the initial strength. Let N represent the number of cycles to failure at stress level ó$_i$, and n the number of cycles experienced at this level. Let ó$_0$ represent the static strength of the material. The slope of the degradation line is then

$$m = \frac{s_i - s_0}{N} \tag{3}$$

Therefore, at any number of cycles during the stressing of this component, a linear residual strength degradation (LRSD)[9] model will yield residual strength as a function of n as:

$$s_R = s_0 + \frac{s_i - s_0}{N} * n \tag{4}$$

which is represented graphically in Fig. 14. Also represented is a nonlinear degradation path.

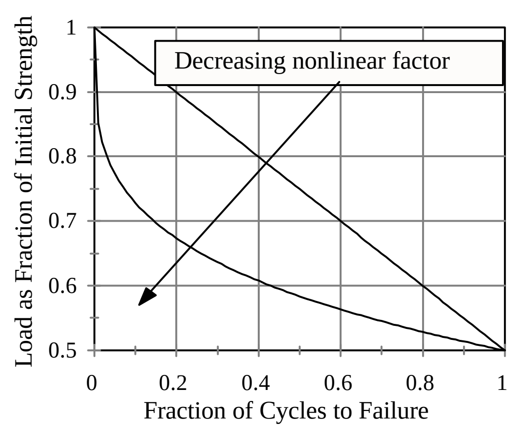

Figure 14. Residual Strength Degradation

The corresponding nonlinear model[3,4] is

$$\sigma_R = \sigma_0 + (\sigma_i - \sigma_0)*\left(\frac{n}{N}\right)^{\nu} \quad (5)$$

where: σ_R = residual strength at n cycles
σ_0= static initial strength (tensile or compressive)
σ_i=applied stress in fatigue
N=number of cycles to failure at the stress level of σ_i
ν=nonlinear factor, a value of ν=1 reduces equation 5 to the linear degradation model of equation 4.

The nonlinear factor affects the shape of the prediction line for the strength degradation (Fig. 14). Values less than one cause a prediction of more damage in the early component life; conversely, values greater than one would predict more of the damage to occur later in the life of the component. Upon investigating the results displayed in Figs. 15 and 16, factors less than one were considered appropriate.

Model Comparison With Data

Figs. 15 and 16 depict the results of strength degradation tests for various maximum applied stresses and for the two R values of 0.1 and 0.5.

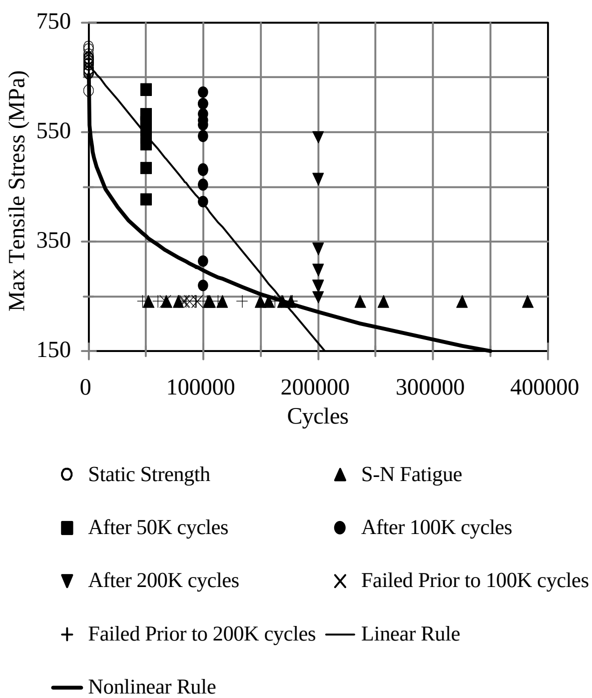

Figure 15, Residual Strength, R = 0.1

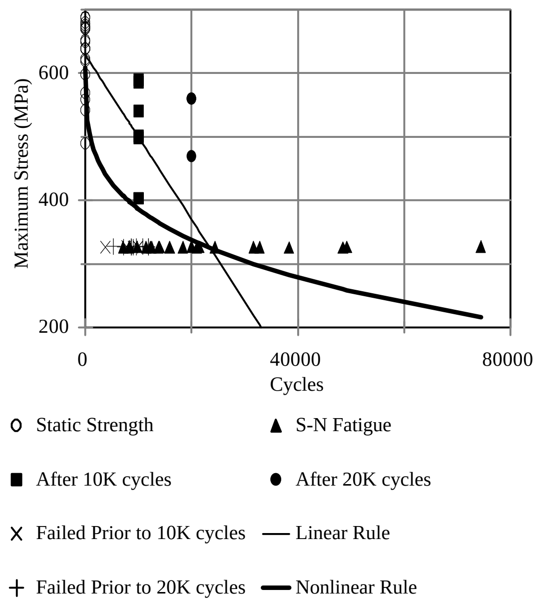

Figure 16. Residual Strength, R = 0.5

While the data are complicated by premature failure during cycling of some specimens prior to residual strength testing, the linear and nonlinear models provide reasonable agreement with the data.

Fig. 17 depicts the lifetime predictions for Miner's, LRSD, and NRSD rules. The nonlinear factor, ν, utilized in these calculations was 0.265, which was selected for fit.

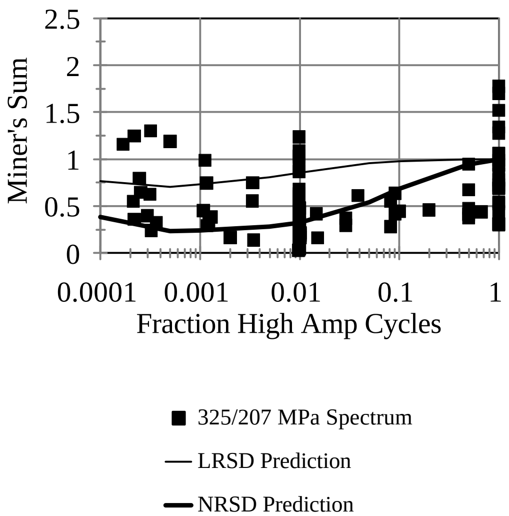

Figure 17. Residual Strength Degradation Lifetime Predictions

In all cases, the nonlinear rule provides better prediction than the other two rules investigated. This is also true for the multi-block spectra as summarized in Tables II and III. (Preliminary testing in compression shows similar results to Fig. 17, with the same nonlinear factor.)

Figs. 18 and 19 show comparisons of the Mod 1 spectrum test results with the three damage rules. For this spectrum there is little difference between the three rules

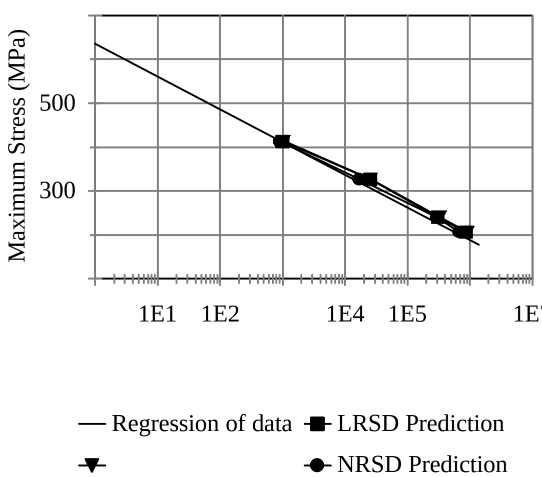

Figure 18. Mod 1 Spectrum Lifetime Prediction R = 0.1

and they are all reasonably accurate at lower load levels.

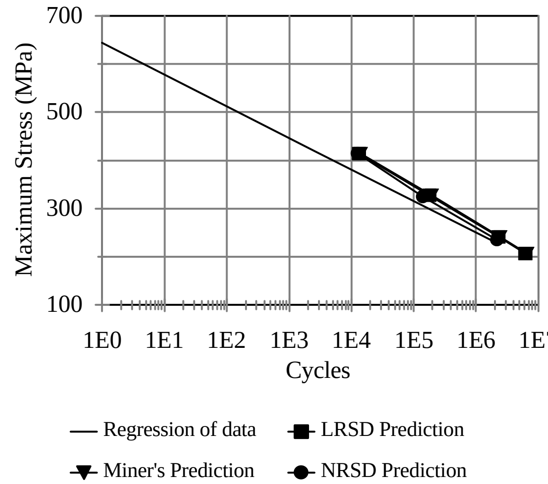

Figure 19. Mod 1 Spectrum Lifetime Prediction R = 0.5

Figure 20 shows that choice of the model is more important for the Mod 2 spectrum, with a single higher load. The nonlinear model fits the data from Fig. 13 much more accurately, particularly at higher stresses. As the maximum stress (and other stresses) is reduced, the models tend to converge.

Generally, as a spectrum includes a greater

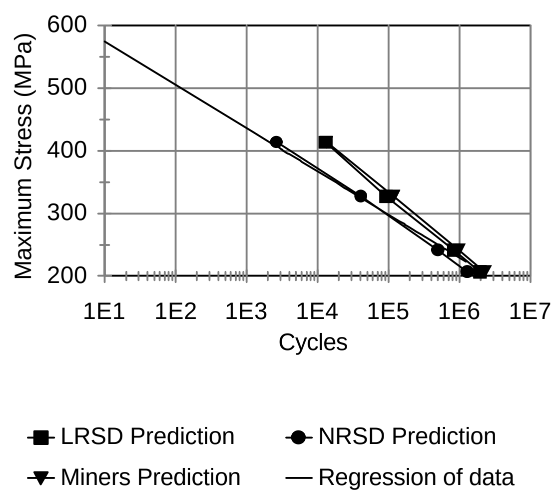

Figure 20. Mod 2 Spectrum Lifetime Prediction R = 0.1

difference in load levels, the damage rule becomes more important. This is illustrated in Fig. 21 which shows predictions for two-block 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.

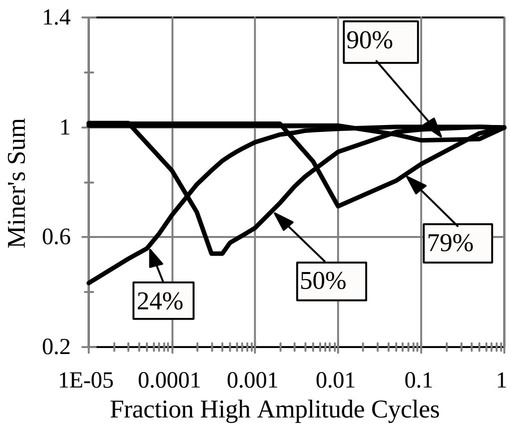

Figure 21. Two-Block Load Level Sensitivity
Low-Block Amp as % of High-Block Amp

CONCLUSIONS

Spectra involving two or more different stress levels generally result in lifetimes less than that predicted by Miner's sum. Better agreement can be found by the application of residual strength degradation based rules. Although the nonlinear rule introduces an unknown parameter that must be determined experimentally, it does provide a better prediction of lifetimes than the linear model. Sequencing effects of the cycles at different stresses is not significant for repeated block loading.

Testing of two modifications of the WISPERX spectrum has demonstrated that the nonlinear residual strength model is more accurate when greater variability is present in the stresses.

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