Strength Degradation and Simple Load Spectrum Tests in Rotor Blade Composites

Rogier P.L. Nijssen*
Delft University of Technology, Knowledge Center Wind Turbine Materials and Constructions, Wieringerwerf, the Netherlands, 1771 MV

Daniel D. Samborsky† Montana State University, Bozeman, MT, 59717, USA

John F. Mandell‡ Montana State University, Bozeman, MT, 59717, USA

Don R.V. van Delft§
Delft University of Technology, Knowledge Center Wind Turbine Materials and Constructions, Wieringerwerf, the Netherlands, 1771 MV

This paper presents comprehensive residual strength data. These data were collected to aid the validation and development of a residual strength based lifetime prediction method. Such a model can be used to predict the lifetime of rotor blade materials subjected to variable amplitude fatigue. Residual strength tests were done on one multi-directional glass-fiber/polyester material, which is representative of the material used in a wind turbine blade. This material has been characterized extensively in the DOE/MSU fatigue database. Both compressive and tensile residual strength tests were performed after three different fractions of the expected lifetime. Residual strength curves were determined in tension-tension, tension-compression, and compression-compression fatigue. In addition, simple load spectra, consisting of two load blocks with different amplitude, were investigated. These results are used, indirectly, to determine the form of the strength degradation model. The results seem consistent with the strength degradation found in the residual strength data.

Nomenclature

S_r	=	Residual Strength after n cycles at S_{max}
S_{r-1}	=	Current residual strength
S_0	=	Initial Strength
S_{max}	=	Maximum load applied in fatigue
n	=	Number of cycles with S_{max}
n_{eq}	=	Number of cycles at S_{max}, which would have led to the same current strength S_r
C	=	Strength degradation parameter

I. Introduction

Fatigue in composites extends to various fields, and is of concern in aerospace, civil, automotive, and marine applications[1]. Most of these applications are traditionally developed under conditions that emphasize the quality of

* PhD-student, Delft University of Technology, Knowledge Center WMC, Kluisgat 5, 1771 MV Wieringerwerf
† Research Engineer, Dept. of Chemical and Biological Engineering, Composites Group, MSU, 301 Cobleigh Hall
‡ Professor, Dept. of Chemical and Biological Engineering, Composites Group, MSU, 301 Cobleigh Hall
§ Assistant Professor, Delft University of Technology, Knowledge Center WMC, Kluisgat 5, 1771 MV Wieringerwerf, the Netherlands

the product with little or no cost constraints. In wind turbine rotor blade manufacturing, the transition from hand-lay-up techniques (low investment, low quality) to semi-automated processing technologies is of fairly recent date.

In contrast with the limited resources that have been available for wind energy research, the complexity of the influence of operating conditions on the economic lifetime is considerable. Wind turbine rotor blades are among the applications of composites that need to withstand the highest number of fatigue cycles. Extensive research has revealed the response of various materials to a large number of constant amplitude fatigue cycles, some of which was consolidated previously[2,3].

In addition, the variability of the wind creates a load spectrum in the blade material, which is far from 'constant-amplitude'. As is the case for metallic materials, the order of the variations in magnitude of the fatigue loads can significantly influence the lifetime of a composite. Recognition of this phenomenon in wind turbine applications can be found in recent work[4,5]. Currently, guidelines require lifetime predictions for spectrum loading fatigue in wind turbine blades to be made using 'Miner's rule', which is a linear model that neglects order effects. Also, the Miner damage parameter has no physical meaning in terms of damage accumulation.

Recent research efforts have focused on improving the lifetime prediction methodology through alternative Goodman diagrams or S-N formulations reflecting better characterization of the material, and by investigating residual strength degradation models as alternatives to Miner's sum[5,6,7]. The nature of the influence of spectral loading, and of the underlying damage mechanisms, is a matter of continuing research.

As investments grow both due to a tremendous increase of the size of turbines being installed over the past few years, and due to the placement of wind turbines in 'wind farms' rather than stand-alone operation, the need for accurate prediction of a turbine's economical life is becoming urgent.

The objective of this paper is to find characteristic parameters for use in a strength degradation model. As the name suggests, such a model tracks the strength of the material over its lifetime. The strength is assumed to degrade in different ways for different loading conditions which are encountered during operation. The residual strength degradation model which is the focus of this paper, is a one-parameter model which can be derived from a relatively simple mathematical model. Although predictions using this type of model have been made frequently, sometimes augmented with statistical considerations[8], there are few experimental results to corroborate the choice of degradation parameter, especially in wind turbine materials[9]. The main reason for this is allegedly the time-consuming experimental effort that is associated with determining this parameter.

This paper deals with finding the nature of strength degradation in a semi-empirical way. A test program was defined, consisting of static, constant amplitude fatigue, residual strength, and block tests. After a discussion of the aforementioned strength degradation model, we will discuss our test program in more detail. The results of this test program are presented and analyzed to find values for the strength degradation parameter.

II. Strength Degradation Model

As an alternative to Miner's sum, a residual strength model not only predicts failure, but it also predicts the loss of strength over the lifetime of the component. A common formulation of a residual strength degradation model is[4]:

$$S_r = S_{r-1} - (S_0 - S_{\max})\left(\frac{n + n_{eq}}{N}\right)^C \tag{1}$$

The parameter C describes the nature of strength degradation: linear degradation, early degradation, or 'sudden death', see Fig. 1. The value of parameter C must be determined experimentally. This is a considerable task, since the possibility can not be dismissed, that this parameter is a function of various parameters, such as material system, R-ratio (ratio of minimum to maximum stress in a fatigue signal), frequency, etc. The large experimental effort that is associated with obtaining a statistically significant dataset has kept researchers from determining this parameter and its functional relationships, especially on wind energy composites. Therefore, only limited data are available to compare with the present results.

Some results may be expected from the ongoing OPTIMAT project, where residual strength and spectral loading are investigated in some detail, among other aspects of materials fatigue, such as extreme conditions, condition monitoring, complex stress states, etc.[10].

Wahl[5] has produced an extensive dataset containing repeated block tests like the ones described later in this paper. Some residual strength degradation data that are available from his test program suggest a linear or early failure type degradation (tensile strength after tension-tension fatigue). This form has worked well for subsequent spectrum lifetime predictions. Andersons and Korsgaard[9] have published residual strength degradation data on a

glass-fiber polyester composite that was representative for rotor blades, where they studied tensile strength after tension-tension fatigue (R=0.1). The degradation parameter *C* they found was slightly above 1 (viz. 1.33), close to a linear degradation model. In addition, from their data they asserted, that the type of degradation is independent of the fatigue stress level preceding the residual strength test.

Most other residual strength measurements were conducted on aerospace grade materials, mostly carbon fiber based composites, where the strength degradation is less pronounced due to the small slope of the S-N curve. Many of these investigations were instigated by damage tolerance investigations, where residual strength was quantified after impact, or in the presence of a notch, and after a given amount of fatigue damage. Residual strength data where the sign (i.e. tension or compression) of the static test was different from the sign of the fatigue test are very rare. Compressive strength after purely tensile fatigue, or tensile strength after purely compressive fatigue, are not prevalent in the literature, to say the least.

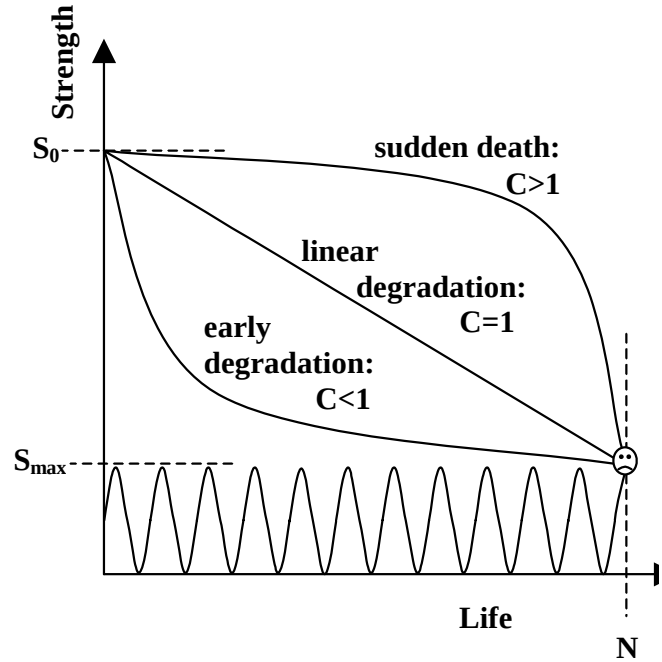

Figure 1. Strength degradation parameter C in Eq. 1

A residual strength degradation model has the advantage of a good physical interpretation of the effects of fatigue loading. One of the important implications of including effective strength degradation-based lifetime prediction methods is, that the residual strength of a blade could be tracked based on bending moment measurements, and assessment of the blade's structural reserves could be made during its service lifetime.

III. Experimental Program

A. Material, Test Specimen, and General Conditions

A single material was used in the present study, which was a multi-directional glass-fiber/polyester material, representative for the material used in a wind turbine blade. This material is designated DD16 in the DOE/MSU fatigue database, which contains a large quantity of information on this particular composite. Some 9000 test results extensively characterize this material in terms of static strength, constant amplitude fatigue behavior, design details, etc.[2]. It has also been used in the study by Wahl[5] on spectrum fatigue, so it was an excellent candidate material for the present investigation.

The material was manufactured in plates in a vacuum assisted resin transfer molding (VARTM-)process, in a [90°, 0°, ±45°, 0°] symmetrical lay-up. For the R=-1 and R=0.1 tests, the specimens were machined into a dog-bone shape using a pin-router set-up, and tabs were applied using a Hysol EA 9309 2NA QT two-component adhesive, and post-cured in an oven at 70 ° C for 3 hours. While curing, pressure was applied on the tabs using mechanical clamps.

For the compression-compression (R=10) fatigue tests, the dogbone geometry was found to be inappropriate and a parallel-sided specimen with no tabs was used successfully. In both geometries, the 90° layers on the specimen surfaces were believed to aid the load introduction by the grips. Fig. 2 shows both specimens.

Having specimens of geometries introduces an extra variable: influence of specimen geometry. Unreported tests in tension-tension fatigue on parallel sided DD16 specimens typically had half the fatigue life of identical tests (same stress level, testing machine, and size of dataset) on dog-bone specimens. Alledgedly, this was due to the stress introduction by the grips, which is more benign in the case of the dogbone specimen. In both geometries, damage after failure in tension-tension fatigue was extensive and over the entire gauge section. Thus, the initiation of the damage could not be seen from the failed specimen.

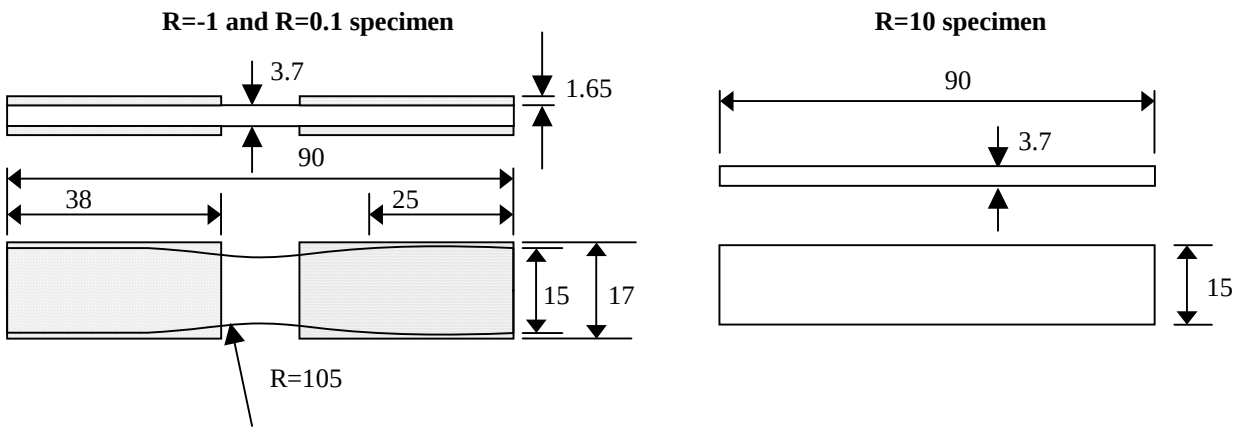

Figure 2. Test specimens

This test program was designed to be self-contained, i.e., the mean life required for stopping a fatigue test at a given damage level was determined using failure data from specimens obtained from the same plate that were tested in the same machine to the same stress level. No interpolation of S-N curves or previously acquired DD16 data have been used in this program, although the S-N data are consistent with results on specimens with the same geometry found in the DOE/MSU database.

The nominal expected lifetime in the fatigue tests was either 1000 cycles or 100,000 cycles. The tests were performed for tension-tension fatigue (R=0.1), compression-compression fatigue (R=10) and tension-compression fatigue (R=-1).

Test frequencies were 1 Hz for the high stress level ('level 1'), and 3 Hz for the low stress level ('level 2'). Static tests were performed at a displacement rate of 12.5 mm/s (0.5 in/s). For these tests, two servo-hydraulic machines were available. An Instron 8501 ±100 kN (ca. 25 kip) machine was used for all static and residual strength tests and some of the constant amplitude and block tests. An Instron 8872 table-top machine with ±20 kN (ca. 5 kip) maximum load capacity was used for constant amplitude and block tests.

Note that the mean nominal lifetime for any of the stress levels investigated here does not exceed 100,000 cyles, whereas a lifetime that is ten to a thousand times longer would be more representative for a composite in a rotor blade. Due to time constraints, the number of cycles for the mean lifetime had to be kept relatively low. Despite the constraints on the program, a total of some 500 specimens were prepared and tested in the course of this project thusfar. Load spectrum tests were still ongoing at the moment this paper was written.

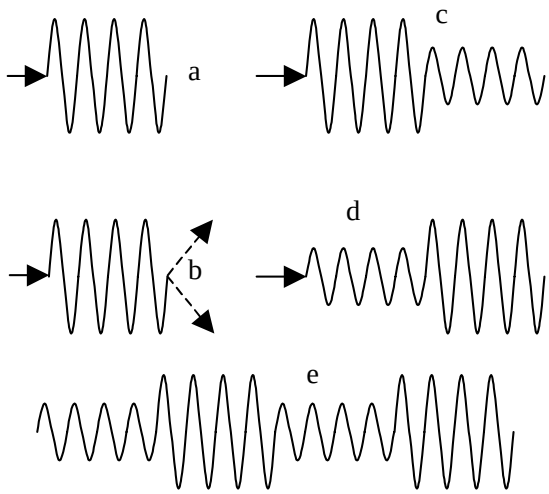

Figure 3. Load sequences for different test types: Constant Amplitude (a); Residual Strength (b); High-Low (c); Low-High (d); repeated block test (e)

B. Residual Strength Tests

Residual strength tests are static tests on a specimen that has been subjected to fatigue loading, see Fig. 3. In order to obtain as many data as possible to model strength degradation due to a realistic spectrum, both compressive and tensile residual strength tests were performed at three fractions of the expected lifetime, viz. 20%, 50%, and 80%. After subjecting the specimen to a number of fatigue cycles corresponding to these fractions of the mean lifetime (which had been established for that particular stress level and R-ratio by a dedicated dataset of nominally 20 specimens), the fatigue test would be stopped at the mean stress level, and either a compression or a tension strength test would be performed, at a displacement rate in the same order of magnitude as the fatigue test had been. The maximum force attained in this test was recorded along with the number of cycles.

A large number of tests was needed to model residual strength degradation. In addition to the abovementioned numerous residual strength tests, the test program includes baseline static and fatigue tests. As a result, testing time was relatively long. Moreover, test progress was hampered by the many premature failures that occurred during the residual strength tests. This was not surprising, since the constant amplitude fatigue tests showed a scatter of the order of one decade (which is commonly observed in this type of material). Assuming a Normal distribution for the fatigue life data, this means that some 45% of all specimens should fail before 80% of the mean lifetime. Thus, the experimenter should anticipate a loss of roughly half of the specimens prior to testing at this lifetime fraction.

C. Block Tests

In addition, simple load spectra consisting of two blocks were performed to aid in the quantification of the degradation parameter. Contrary to Miner's sum, which is by definition equal to unity at failure, the residual strength degradation model can predict failure at Miner's sum of greater than 1 for so-called High-Low tests (HL), where one block of cycles is followed by a block of cycles with a lower amplitude, and smaller than unity for Low-High tests (LH), where the second block is with cycles of a larger amplitude (see Fig. 3). This deviation is classically seen by most experimenters in this type of 'Two-block tests', which is a rather academic type of spectrum[11]. The degree in which Miner's sum deviates from unity depends on the strength degradation parameter C, so it should be possible to derive this parameter from the two-block results.

For the sake of clarity, this last remark needs to be expanded a little. The smaller *C* is, the larger Miner sums are for HL tests, and the smaller they are for LH tests. As the parameter *C* increases, the Miner's sum for a two-block test tends to unity. It is a common misconception, that if C=1, equation (1) gives the same prediction as Miner's rule (i.e. Miner's sum is 1 for both HL and LH sequences, regardless of the length of the first block). Rather, a value of *C* much larger than 1 leads to predictions which are close to Miner's rule. If residual strength tests find, that the strength degradation is of the 'sudden death' type, the two block test results are likely to be close to a Miner's sum of 1 for that particular R-ratio and mean stress.

A schematic is shown in Fig. 3. Both High-Low, and Low-High tests were conducted in this program, though not for the tension-tension case. Another type of test, the repeated block tests, was also done, especially for R=-1. These tests can be used to quantify the effect of frequent transitions between load levels.

IV. Test Results and Analysis

D. Residual Strength Tests

The results of the residual strength tests are shown in Figs. 5 through 8. An explanation is given in Fig. 4. Three distinct sections of data are visible. On the ordinate, a band of data represents the initial properties in terms of strength, these are the 'static data'. A horizontal band of data at the maximum stress of the fatigue cycles (s_{max}) , represents the constant amplitude fatigue data. All data above the constant amplitude fatigue data, but right of the ordinate, are the residual strength data. As was explained earlier, the residual strength was tested at fixed fractions of the mean lifetime, resulting in vertical bands of data at these lifetime fractions.

Note, that not all residual strength data are exactly on 20%, 50% or 80% of the lifetime. In some cases, additional constant amplitude tests were done after some residual strength tests had already been carried out. This typically caused the vertical residual strength data bands to shift a few percent left or right, when the new 'mean lifetime' was taken into account. Some tests ran past the predetermined number of cycles (some of the tests had to be stopped manually, resulting occasionally in these 'run-overs'), which are visible as the data points outside the vertical bands. Nevertheless, these are valuable data and they were included in the analysis.

In the legend of the plots, the number of premature failures is compared to the total number of attempts to do residual strength tests. In most cases, the ratio of these numbers is indeed close to 45%, as was theorized in a previous paragraph. However, in some cases there were extremely few premature failures (viz. tensile residual strength after tension-tension fatigue at level 1 (Fig. 5), and tensile residual strength after tension-compression fatigue at level 2 (Fig. 6)). This could be a matter of small sample statistics, or on the other hand, it could mean that the average number of cycles at that stress level is higher than measured in the constant amplitude tests. This, in turn is not likely, since minimum sample size in all constant amplitude tests was 15 samples.

How can the value of the strength degradation parameter be extracted from these figures? In the light of equation (1), static tests can be considered as residual strength tests with n_i=0 fatigue cycles; fatigue tests are residual strength tests after N_i fatigue cycles. The subscript i in this case denotes the specimen, and not the mean, lifetime. As was schematically shown in Fig. 1, the strength degrades from the initial strength, until the residual strength is exceeded by the maximum occurring stress in the fatigue signal, at which moment specimen life ends.

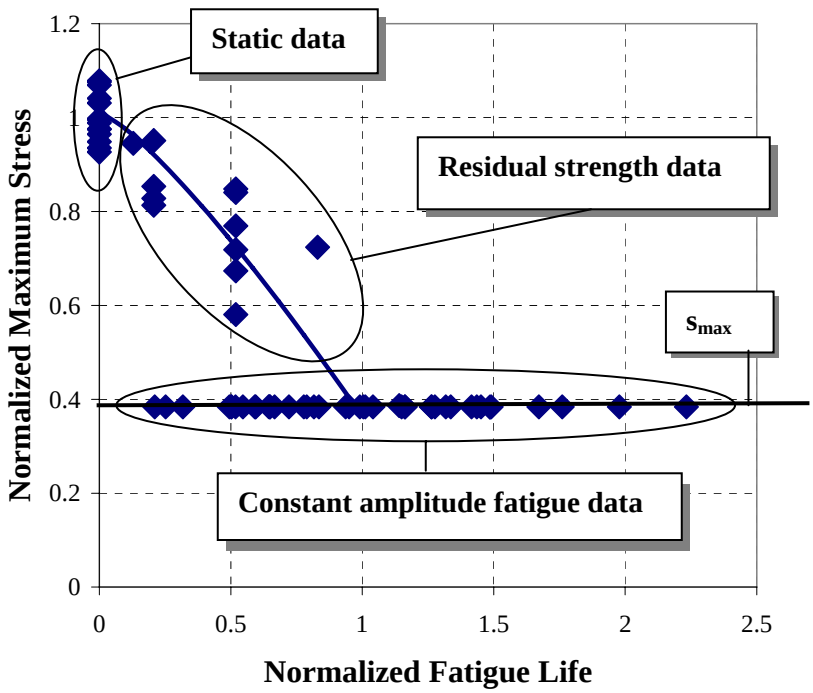

Figure 4. Key for Figs. 5-8

This is roughly seen from the results; the bands of residual strength tests are between the static results and fatigue tests, respectively. From a first appraisal of the results, it seems that the residual strength tests of same sign as the fatigue tests show a rapid degradation; after 50% of the mean life, the strength has decreased by 10-30 % in most cases. In the case of level 1 tensile strength, this strength degradation occurs as early as 20% (the lowest lifetime fraction considered here). In terms of Eq. 1, this suggests a low value of C. In the case where the sign of the residual strength test is opposite to that of the fatigue test, i.e. for tensile strength after compressive fatigue and for compressive strength after purely tensile fatigue, the strengths do not seem to degrade until a high fraction of the lifetime. This suggests a high value of C.

E. Best Fit for strength degradation parameter C

For some of the results, the degradation parameter can be deduced quantitatively if we make the assumption known as the Strength-Life-Equal-Rank-Assumption, or SLERA. This assumption implies, that the rank of strengths and lives when comparing a static dataset to a set of fatigue data is equal. Thus, specimens that have produced above-average static strength results, would have been likely to have reached above average fatigue lives, and vice versa. The opposite is true for specimens in the lower tails of the strength or life distributions. This assumption is fairly common in the relevant literature, and the current results do not seem to be inconsistent with it.

Extending this assumption to the residual strengths means that the higher residual strengths in a dataset at a particular lifetime fraction would have come from relatively strong specimens, compared to the lower residual strengths in the same dataset.

Given the SLERA, each residual strength measurement can be linked to a static strength and a corresponding fatigue life under the assumption of a value for the strength degradation parameter *C*. Via an iterative procedure, where *C* is varied, a set of static data and a set of fatigue data can be generated which matches a parameter corresponding to the experimental static and/or fatigue results best. Such a parameter could be mean fatigue life, standard deviation of the fatigue life, or the mean and standard deviation of the static experimental results, or by matching Weibull parameters instead of parameters of the Normal distribution. In this case, the *C* was found which gave the best fit of the mean fatigue life. This value of *C* is then considered the best fit strength degradation parameter, and the corresponding strength degradation is plotted in Figs. 5 to 8. Generally, the parameters have values close to 1 for tensile strength, and ranging between 2 and 4 for compressive strength.

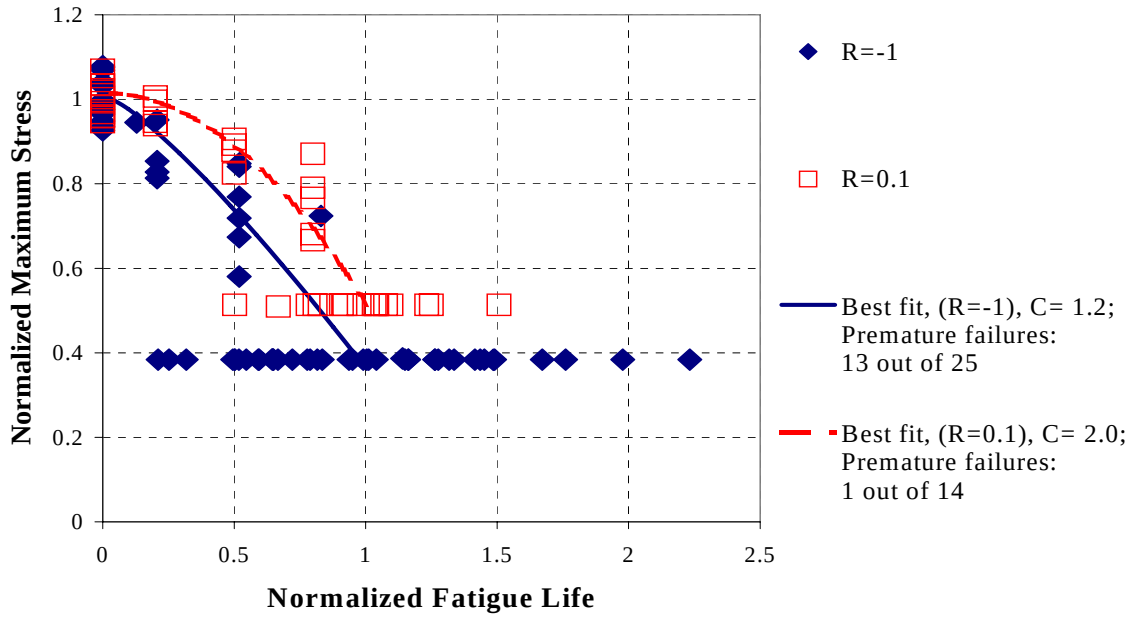

Figure 5. Tensile residual strength plot, nominal lifetime 1000 cycles (level 1)

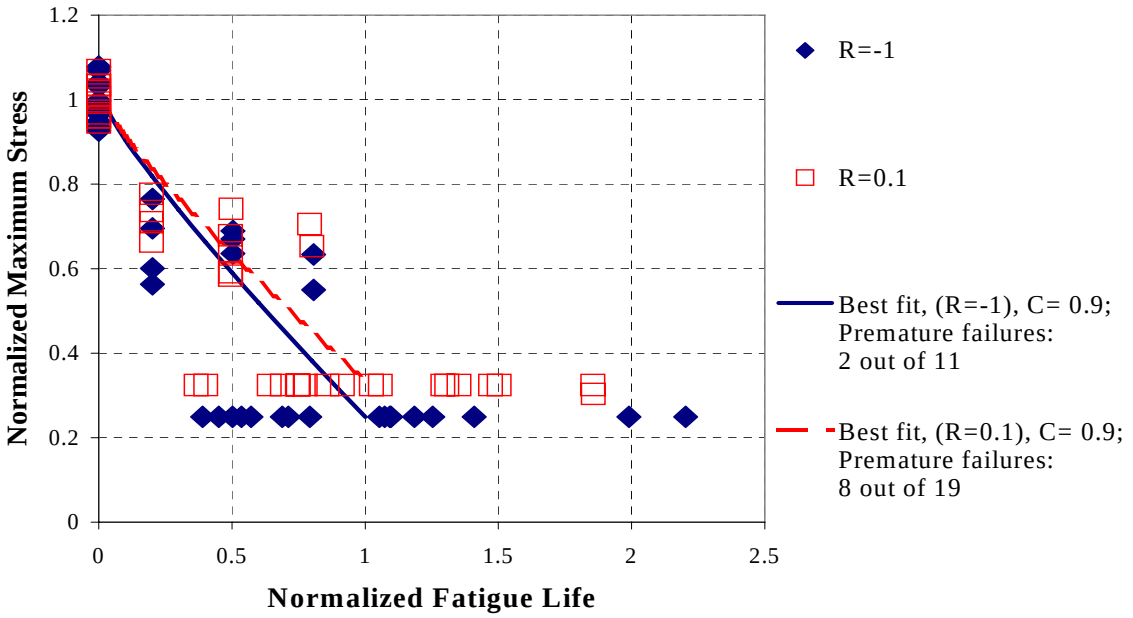

Figure 6. Tensile residual strength plot, nominal lifetime 100,000 cycles (level 2)

F. Block Test results

The High-Low and Low-High test results are displayed in Figs. 9 - 11. In addition, the results of the repeated block tests are presented in Fig. 12. Tests, where the specimen failed prior to reaching the end of block 1, were considered 'premature failures' and are not shown in these graphs.

There are several things to be noticed in these graphs. First of all, there is considerable scatter in the Miner's sums. This is no surprise, as in the constant amplitude tests, the Miner's sums typically varied by approximately a decade. The limited number of data points that are available and their relatively large scatter do not facilitate conclusive analysis of these results. Also, as was mentioned before, the residual strength degradation model of equation (1) is capable of predicting Miner's sums strictly larger than unity for High-Low sequences and Miner's

sums strictly smaller than unity for Low-High sequences. In fact, if the value of the degradation parameter is equal for both sequences, equation (1) is not capable of producing predictions for HL- tests that are smaller than unity, or predictions for LH-tests that are larger. Following this qualitative argument with the results presented in Figs. 9 - 11, there seems to be a tendency for Miner's sums to increase as the length of the first block increases. As shown in Fig. 10, this observation is consistent with a constant C for each stress level. Note, that an arbitrary value of 0.2 was chosen for C in this prediction, and that a larger C would lead to a more horizontal line. Also note, that the prediction produces a singularity at $n_1/N_1 = 1$: at this point, Miner's sum should be 1 since it represents a one-block test (i.e. an ordinary constant amplitude test). This singularity gets smaller for larger values of C.

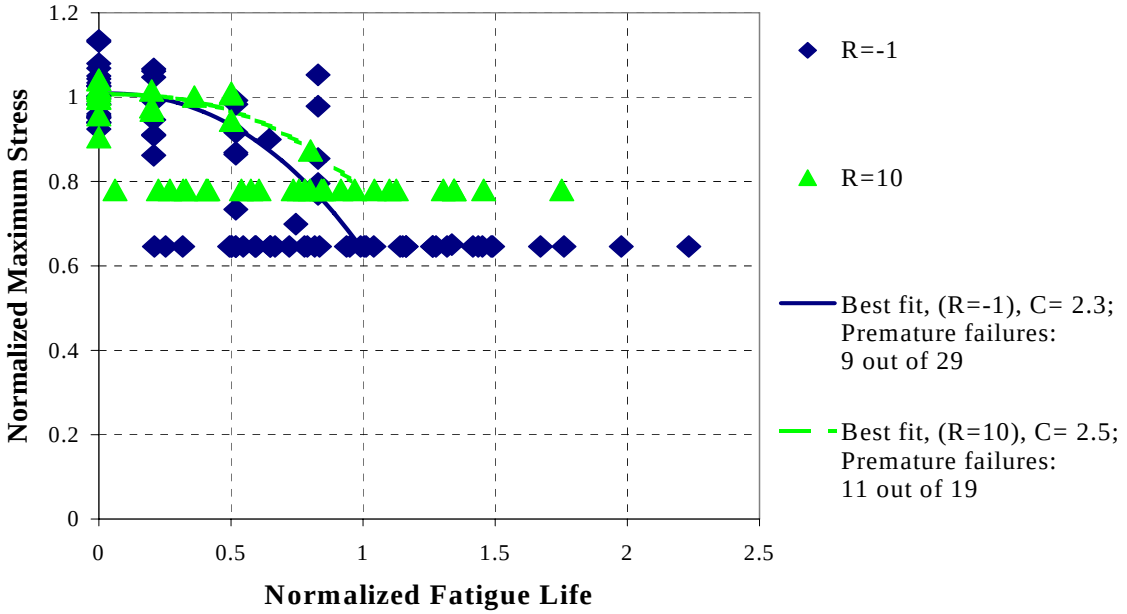

Figure 7. Compressive residual strength plot, nominal lifetime 1000 cycles (level 1)

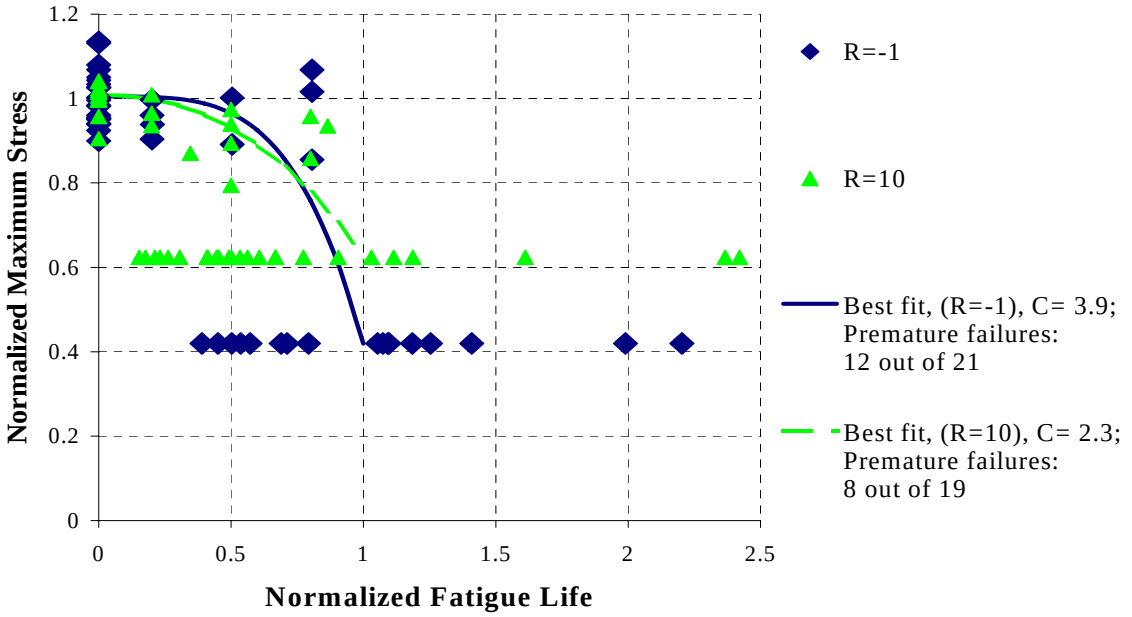

Figure 8. Compressive residual strength plot, nominal lifetime 100,000 cycles (level 2)

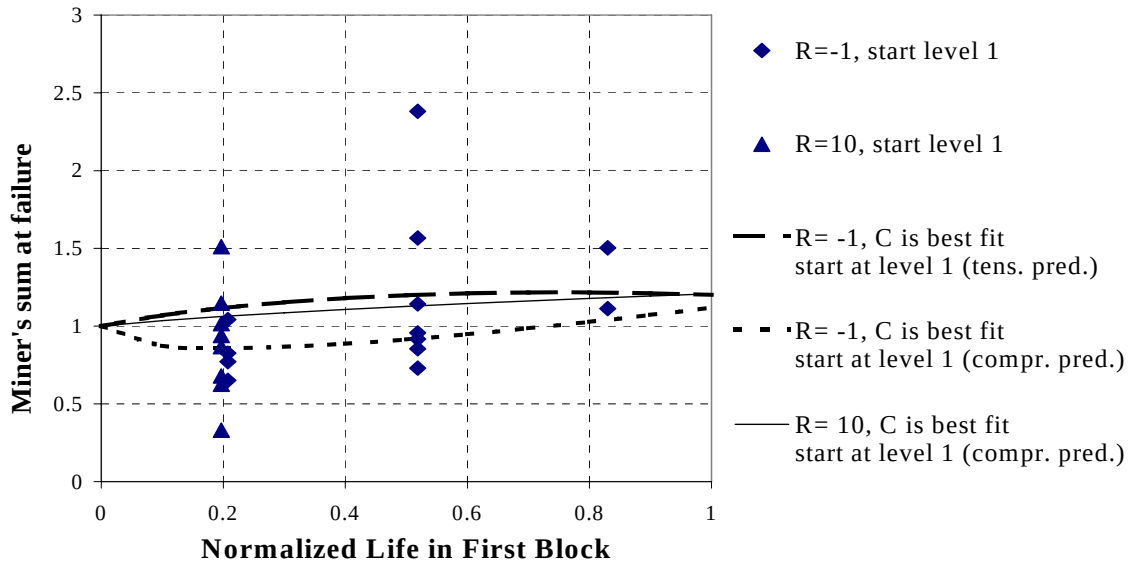

Figure 9. High-Low Two-block tests

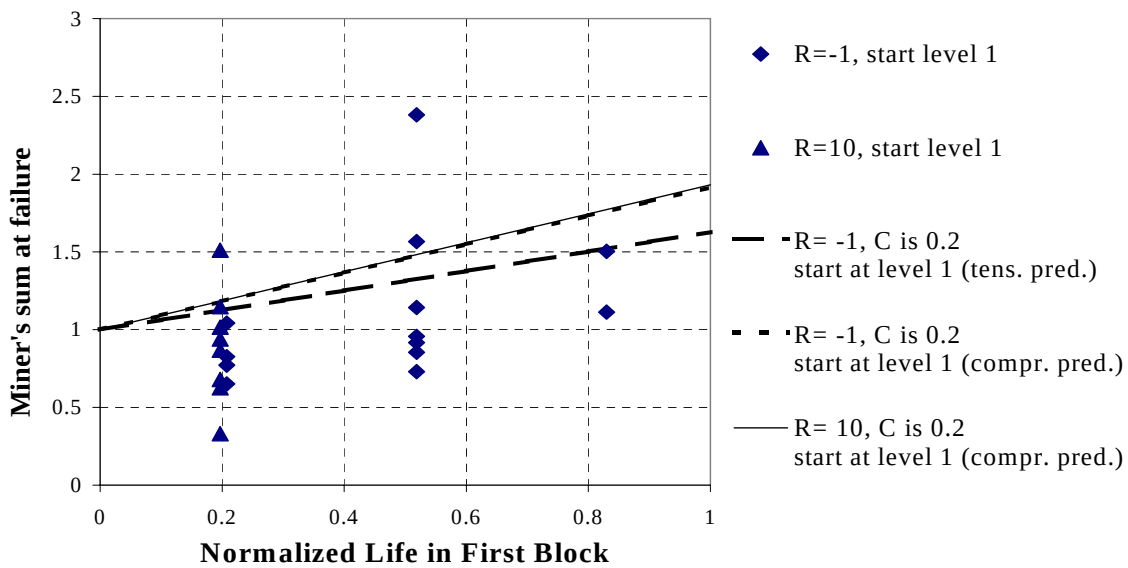

Figure 10. Prediction using a single value for C, High-Low Two-block tests

In contrast with a single value of C for both stress levels in the two-block sequence, the results also show Miner's sums smaller than one for the HL tests and Miner's sums larger than one for the LH tests, at least tentatively. This can not be explained by a single value of C for both blocks. Figs. 9 and 11 also show the predictions that were made using the values of C from Figs. 5 to 8, and these predictions do cater for Miner's sums < 1 for HL and >1 for LH tests.

Two additional remarks on these predictions are in order: there are two ways of predicting HL/LH-life for R=-1, viz. tracking the tensile residual strength to tensile failure, or tracking the compressive residual strength until compressive failure. Most of the R=-1 block tests failed in compression, so it seems most appropriate to track compressive strength only. Nevertheless, R=-1 is close to the R-value that bounds compression and tension

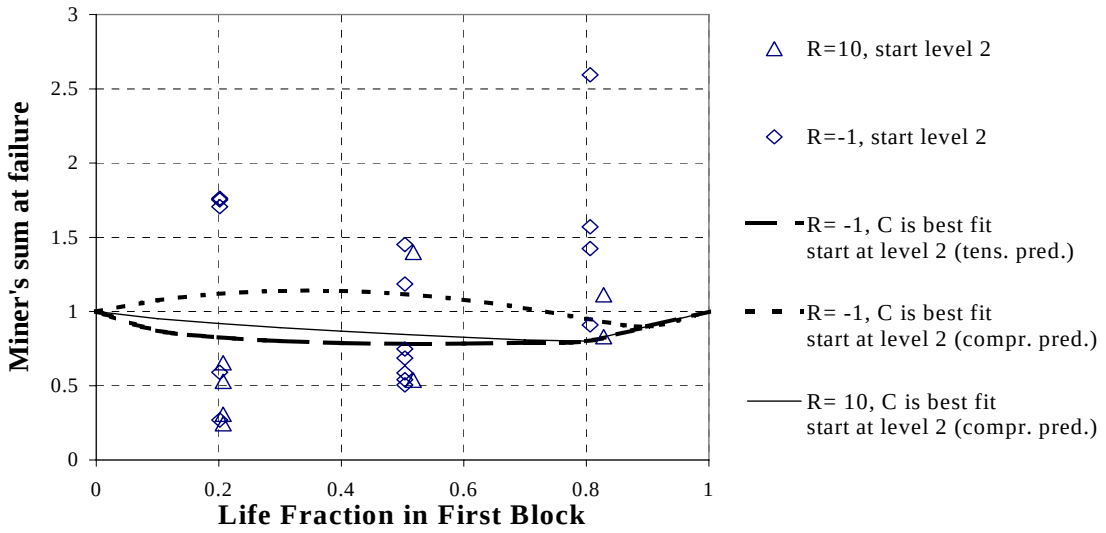

Figure 11. Low-High Two-block tests

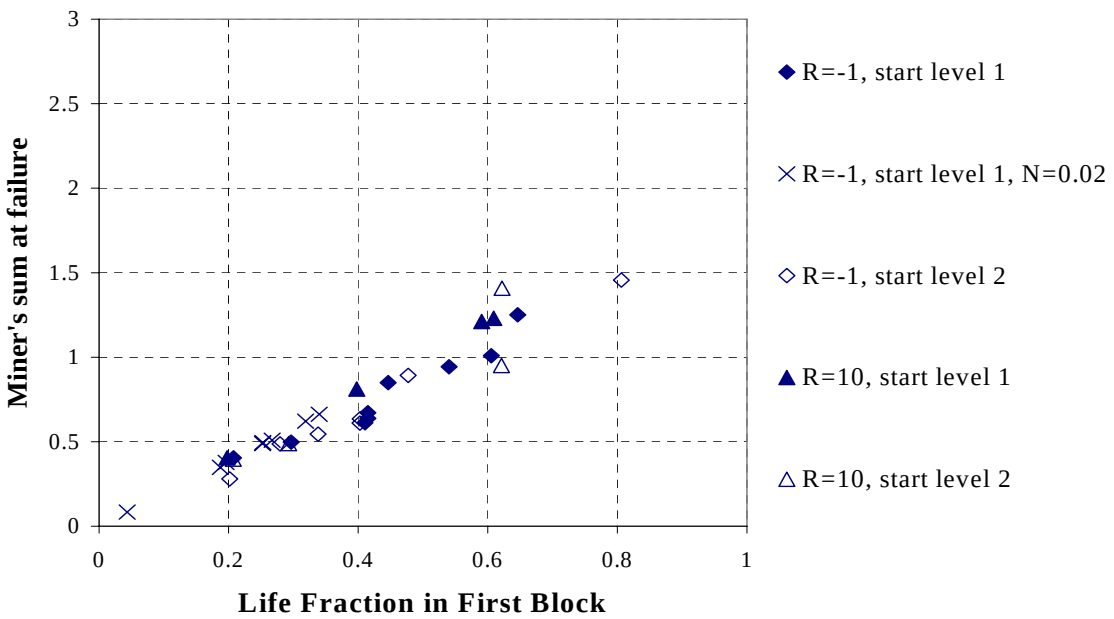

Figure 12. Repeated block tests

dominated fatigue (the exact R-value is larger than R=-1, depending on the asymmetry of the Goodman Diagram), so the prediction tracking tensile strength is also shown.

Secondly, in the case of Low-High tests, a failure may occur in the first cycle of the second block, since there the stress suddenly increases compared to the previous and residual strength may have dropped below the maximum stress in the second block. The predictions show a discontinuity at this point. Fig. 11 shows such a discontinuity at around 0.8, where the Miner's sum at failure is equal to the normalized life in block 1. The smaller *C* is, the shorter the block length of the first block is where this discontinuity occurs. For small Cs, the strength degrades rapidly in the first phase of specimen life, increasing the chance of failure early in the second block.

As for the repeated block tests, predictions listed in the table show that Miner's sum at failure is smaller than unity in all cases. This is independent of block length (as long as blocks are sufficiently small so that no two-block-type tests occur). The larger the parameter C, the closer the predictions are to Miner's sum of 1. The predictions for the best fit values of *C* (from Figs. 5-8) are close to a prediction with *C* = 2 (the best fit values were also close to 2).

Indeed, in Fig. 11, most tests result in Miner's sums below 1. As can be expected, Miner's sum at failure is independent of the level in the first block.

One aspect of the results is puzzling however. For small block lengths of 2% of the expected lifetime, the average Miner's sum is roughly half of tests with blocks that are ten times as long. This could mean, that the number of transitions between blocks might induce extra damage. Inherent to the machine controls, some overshoot typically occurs between blocks, but this is by far not large enough to account for such a considerable reduction in life. Perhaps a type of 'mix damage', as proposed in Ref. 12, should be considered.

V. Concluding Remarks

The data that were collected are consistent with degradation parameters *C* larger than, or close to, a value of one. Compressive residual strength data suggested a 'sudden-death'-type strength degradation, whereas considerable tensile strength loss is apparent in early life. After compression-compression fatigue, both tensile and compressive strength reduction are relatively small for large fractions of the expected life.

Evaluation of the residual tensile strength degradation parameter is not straightforward for two cases. Tensile strength after strictly compression fatigue, and compressive strength after purely tensile fatigue, can not be interpreted by the residual strength formulation in its current form. A modification is necessary for these cases.

The results of the two-block tests and repeated block tests are consistent with the residual strength results, although they do not provide significant aid in quantifying residual strength degradation. Limited results indicate possible need to account for the number of transitions between stresses, however, further testing is necessary to check this and to derive corrections for this.

Additional research should investigate mixed R-ratio effects and other variable amplitude-effects that were outside the scope of this current work. Also, damage characterization after fatigue, and the relationship between damage and residual strength should be evaluated, e.g. by inspecting specimens in a microscope prior to failure.

Future research on other specimen geometries, matrix/fiber materials, and lay-ups should reveal if the nature of strength degradation is universal or that it somehow depends on these (or other) parameters.

VI. Acknowledgment

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