Fatigue life prediction of rotor blade composites: Validation of constant amplitude formulations with variable amplitude experiments

T Westphal and R P L Nijssen
Knowledge Centre WMC, Kluisgat 5, 1771MV, Wieringerwerf, The Netherlands
E-mail: t.westphal@wmc.eu

Abstract. The effect of Constant Life Diagram (CLD) formulation on the fatigue life prediction under variable amplitude (VA) loading was investigated based on variable amplitude tests using three different load spectra representative for wind turbine loading. Next to the Wisper and WisperX spectra, the recently developed NewWisper2 spectrum was used. Based on these variable amplitude fatigue results the prediction accuracy of 4 CLD formulations is investigated. In the study a piecewise linear CLD based on the S-N curves for 9 load ratios compares favourably in terms of prediction accuracy and conservativeness. For the specific laminate used in this study Boerstra’s Multislope model provides a good alternative at reduced test effort.

1. Introduction
In wind turbine blades, material and structural fatigue is an important design driver. The operational loads acting on wind turbine blades are variable amplitude in nature. In the experimental characterisation of the fatigue behaviour of a material, constant amplitude loads are used. Life prediction methods relate the variable amplitude loads to the constant amplitude (CA) behaviour.

The fatigue life prediction methods for variable amplitude loading consist of several steps. From the variable amplitude load, described as a sequence of peaks and valleys, a cycle counting method extracts constant amplitude cycles and groups them according to range and mean. Thus, the variable amplitude load can for example be expressed as a histogram with range, mean, and number of occurrences. Using the characterisation of the constant amplitude fatigue behaviour, the fatigue damage due to these various cycles is calculated. The constant amplitude fatigue behaviour is typically characterised using a power law to describe the stress (S) – life (N) behaviour for a given load ratio (R, ratio of minimum to maximum applied load) and a Constant Life Diagram (CLD) formulation to interpolate between load ratios. Finally a damage summation rule is used to calculate the total damage of the combined cycles. Of these steps the selection of the CLD formulation is one of the most influential steps [1].

For the experimental comparison of the behaviour of materials and structures under variable amplitude loads, standardized load spectra have been developed. For wind turbine materials the WISPER spectrum [2] was developed in 1992, along with its shortened version WISPERX. These load sequences are based on the loading typical for the turbines of that time. Because wind turbine size has increased dramatically since then, the nature of the loads has changed. Within the OPTIMAT project the New Wisper spectrum [3] was developed, typical for MW size pitch controlled turbines.
Next to the comparison of behaviour under variable amplitude loads, results from spectrum tests can also be used to compare and validate life prediction methods. Such a comparison requires a considerable amount of experimental data. Next to spectrum test results also a vast amount of constant amplitude fatigue data for the same materials is needed. The constant amplitude data needs to be suitable to derive the parameters for all the CLD formulations in the comparison.

Within the Upwind project [4] a glass-epoxy UD laminate typical for wind turbine blade material was characterised in detail. The fatigue behaviour was characterised for 9 different load ratios, providing a dataset of approximately 200 fatigue tests which can be used to derive the parameters for many CLD formulations.

Within the current research variable amplitude fatigue tests were performed on specimens made from the same batch of laminates that were used for the Upwind project. Using the data from Upwind, these experiments are used to investigate the effect of several CLD formulations on life prediction under variable amplitude loads. Four CLD models will be compared: the Goodman diagram, a piecewise linear CLD based on three R values, a piecewise linear CLD based on 9 R values, and Boerstra’s model.

2. CLD models

For the experimental characterisation of the fatigue behaviour of composite materials, constant amplitude fatigue tests are used. In these tests the dependence of the number of cycles to failure (N) on the applied stress (S) is typically derived at a constant R ratio. A power law curve (a straight line on a log-log scale) is fitted to the test data to describe the behaviour:

\[ \log N = A - m \log \sigma_a \]  

In which \( A \) is the intercept and \( m \) is the slope parameter of the S-N curve.

In the fatigue experiments, cyclic loads are chosen leading to cycle counts ranging from several hundred up to several million. The curves fitted to these experiments need to be extrapolated to higher cycle counts for design purposes, as the actual cycle counts in wind turbine blades are estimated to be in the range of \( 10^8 \) to \( 10^9 \). Performing experiments up to 600 million cycles, van Delft et al. [5] showed that the power law curve provides a good prediction for extrapolation to high cycle counts and that no fatigue limit is present, even for the high cycle counts encountered in wind turbines.

To provide predictions for loading at load ratios for which no description is available from experiments, a CLD model is used. These models aim to quantify the effect of mean stress, or load ratio, on fatigue life. In this study four CLD models will be compared: the Goodman diagram, a piecewise linear CLD based on three R values, a piecewise linear CLD based on 9 R values, and Boerstra’s model. The formulations of these models are given below.

2.1. Goodman Diagram

The Goodman Diagram is based on the S-N curve for R = -1 (zero mean stress) and the static tensile and compressive strengths. For a given stress amplitude \( \sigma_a \) at mean stress \( \sigma_m \) the corresponding stress amplitude at \( R = -1 \) is obtained using:

\[ \sigma_{a,R=-1} = \sigma_a \cdot \left(1 - \frac{\sigma_m}{UTS}\right)^{-1} \]  

Where UTS is the static tensile strength of the material. For compressive mean stresses the tensile strength in (2) is replaced by the static compressive strength. The allowable number of cycles is then obtained using:

\[ \log N = A - m \cdot \log(\sigma_{a,R=-1}) \]

The Goodman diagram is the best known and most commonly used, particularly for metals. Its construction is based on the S-N curve for load ratio R = -1 (zero mean stress) and uses linear interpolation to the static tensile and compressive strength. However, the Goodman diagram does not provide a good match to experimental data for composite materials due to the considerable influence
of mean stress. To account for this without further complicating the CLD model excessively, the ‘shifted Goodman diagram’ was developed, in which the highest point, that is the highest allowable stress amplitude, is shifted away from \( R = -1 \) (zero mean stress) to the average between tensile and compressive strength. The gain of this approach is at least limited, as the shift is not physically reflecting a change in damage mechanisms involved.

2.2. Piecewise linear CLD

One approach to address the differences between fatigue behaviour in compressive and tensile loading is to use a more detailed CLD formulation, based on S-N data at multiple R values. Apart from \( R = -1 \), \( R=0.1 \) (tensile fatigue) and \( R = 10 \) (compressive fatigue) are common load ratios for tests. In the piecewise linear CLD multiple load ratios are used with linear interpolation between them, as shown in figure 1. For such a CLD individual S-N curves are fitted for all the load ratios for which data is available. Based on the slope and intercept parameters of these S-N curves the equations describing this CLD are given below [11].

Given a series of S-N curves, numbered 1,2,...,n starting from the S-N curve with the highest tensile mean stress and ending at the lowest (compressive) mean stress, the following analytical expressions can be used. Between the tensile axis and the first S-N curve the expected number of cycles \( N \) is given by:

\[
N = \left( \frac{k_1 \left( \frac{UTS}{\sigma_a} + r_1 - r \right)}{UTS} \right)^{m_1} \tag{4}
\]

Where \( m_1 \) is the slope parameter of the S-N curve and \( k_1 \) is the intercept of the S-N curve at \( N=1 \), given by:

\[
k = 10^\frac{\alpha}{m} \tag{5}
\]

\( \alpha \) is the intercept as in (1); \( r \) is the load ratio of mean stress over amplitude stress and related to the load ratio \( R \) by:

\[
r = \frac{1+R}{1-R} = \frac{\sigma_m}{\sigma_a} \tag{6}
\]

In these formulas \( r \) without subscript corresponds to the mean stress and amplitude stress for which the number of cycles is calculated. The \( r \) with subscript refers to the neighbouring S-N curve(s).

For compressive mean stresses the number of cycles is given by:

\[
N = \left( \frac{k_1 \left( \frac{UCS}{\sigma_a} - r_a + r \right)}{UCS} \right)^{m_c} \tag{7}
\]

For sections between two S-N curves, equations explicit in \( N \) can be derived. The allowable stress amplitude for a given mean stress and number of cycles is given by:
Using this equation, the allowable number of cycles for a given mean and amplitude stress can be obtained using a numerical optimisation technique.

Within Upwind, a fatigue analysis of a UD laminate at 9 R values was performed, giving a detailed description of fatigue behaviour. In figure 1 the piecewise linear CLD based on these test data is shown. The test data itself are indicated by the dots. The colour of the lines corresponds to the number of cycles, e.g. the innermost green line indicates the allowable stresses at 10^8 cycles to failure. For the test data the number of cycles to failure is also indicated by the colour of the dots, which are coloured using a continuous spectrum corresponding to the colours of the lines.

**Figure 1. Piecewise linear CLD based on 9 R values from Upwind**

Although providing a detailed description of fatigue behaviour, a drawback of this approach is the experimental effort involved in obtaining the required test data. The CLD shown in figure 1 contains close to 200 data points, with the longer tests taking up to a week to complete (per test). Therefore, when characterising a laminate for design purposes, the number of load ratios and thus the accuracy of the CLD is limited due to practical constraints.

Several models attempt to address this problem by providing a better match to the actual behaviour based on a more limited dataset. Beheshty and Harris [6] used bell-shaped curves to fit the CLD. Kawai [7] proposed a formulation based on a critical S-N curve at a load ratio equal to the ratio of the static compressive strength to the static tensile strength. Boerstra [8] proposed a model based on Gerber’s parabola at a reference number of cycles, and a slope parameter dependent on the applied mean stress.

In a recent study by Vassilopoulos et al. [9] several CLD formulations were compared regarding their ability to predict the constant amplitude fatigue behaviour for arbitrary loading. In their study the piecewise linear CLD compared favourably with respect to consistency and prediction accuracy. Of the other models Boerstra’s model provided predictions that were closest to the piecewise linear CLD.
Based on the Upwind dataset, Westphal et al. [10] showed that Boerstra’s model provided a good fit to the fatigue data and was relatively insensitive to the input data.

2.3. Boerstra’s Multislope model

In the Multislope model, for a given mean stress $\sigma_m$, the allowable stress amplitude $\sigma_{ap}$ at a reference number of cycles $N_p$ is given by (for tensile mean stress, $\sigma_m > 0$):

$$
\sigma_{ap} = \sigma_{ap} \left(1 - \left(\frac{\sigma_m}{UTS}\right)^{\alpha_T}\right)
$$

(9)

Where $\sigma_{ap}$ is the allowable amplitude for $\sigma_m = 0$ and parameter $\alpha_T$ defines the curvature of the line to the static strength. For compressive mean stress ($\sigma_m < 0$) a second curvature parameter $\alpha_C$ is used:

$$
\sigma_{ap} = \sigma_{ap} \left(1 - \left(\frac{\sigma_m}{UCS}\right)^{\alpha_C}\right)
$$

(10)

The allowable stress amplitude at a number of cycles $N$ is derived by using a linear S-N line on a log-log scale:

$$
\frac{\sigma_u}{\sigma_{ap}} = \left(\frac{N}{N_p}\right)^{-\frac{1}{m}}
$$

(11)

The slope parameter $m$ is dependent on the mean stress:

$$
m = m_0 e^{-\sigma_m / D}
$$

(12)

Where $m_0$ is the S-N slope for $R = -1$ and $D$ is a fitting parameter that affects the dependence of the slope on the mean stress. In this study, for the model parameters the values derived in [10] are used: $N_p = 3.86$, $S_{Ap} = 928$, $m_0 = 8.72$, $\alpha_T = 3.11$, $\alpha_C = 0.75$ and $D = 627$.

3. Wind turbine load spectra

Spectrum tests provide a standardised way to validate the performance prediction of materials under variable amplitude loading. Various load sequences exist in fatigue research, most of which have been developed to be representative for a specific application. For wind turbine rotor blades, Wisper and WisperX sequences [2] are the most relevant examples. These load sequences are representative of the loads in a wind turbine blade, and were derived from strain measurements on blades in operation (blade root, flapwise direction). An important notion regarding the WISPER(X) sequences is, that the main intended use is not to represent a design load, but to compare materials in terms of variable amplitude (VA) fatigue response and/or to develop and validate fatigue models.

In the OPTIMAT blades project, a new WISPER-like sequence was developed [3] because it was the general opinion of the project partners, that the WISPER standard VA load sequences were no longer very representative of the load spectrum that a wind turbine blade experiences. This was because of the development in wind turbine size and control algorithms during the ~10 years after the definition of the original WISPER sequences. In other words, the cyclic content of the flapwise strain signal measured near the blade root was expected to have changed, due to changes in technology of various wind turbine components.

In addition, due to increasing turbine blade size, gravity loads had become more important and this influence on the cyclic load content in edgewise direction should be considered in a new standardised load sequence. However, in an early stage of the NEW WISPER development this ambition was discarded because it was not clear how to implement this in a load signal for uni-axial testing.

In [3], copying as much as possible the methodology used in the development of WISPER and WISPERX, a new load sequence was produced, and named ‘NEW WISPER’. The most significant difference in the method, however, is that the last ‘randomisation’ step was not carried out. This randomisation step was performed in Upwind and resulted in the NewWisper2 spectrum [12].
3.1. Load spectrum characterisation

Load spectra are usually specified as a series of peaks and valleys. Using a cycle counting algorithm the peaks and valleys of a variable amplitude load such as a spectrum are converted to constant amplitude cycles of different range and mean. Many cycle counting methods are available [13]. Rainflow counting is a commonly used cycle counting algorithm. In this research, because it deals with repeated load sequences, the simplified rainflow counting algorithm for repeated histories from [13] is used.

Wisper and WisperX each are peak-valley sequences of integer numbers between 1 and 64. These values are multiplied to obtain e.g. a maximum load. Level 25 is the ‘zero-stress’ level, so all peaks/valleys with a number lower than 25 would be scaled to result in compressive loads. One sequence of Wisper consists of a total of 265422 peaks and valleys, or halfcycles. WisperX is a shortened version of Wisper, where all cycles with a range less than 17 have been omitted. In figure 2 scatterplots of the counting results for a Wisper and a WisperX sequence are given. For each combination of means stress level and range, the cycle count (in half-cycles) is indicated by the size and the color of the circles. This is reflected in figure 2 by the absence of the large dots.

![Figure 2. Cycle range and mean distribution for Wisper and WisperX load spectra](image)

In figure 3 the cycle distribution for the New Wisper2 spectrum is given (the cycle distribution for the original NewWisper spectrum would be almost identical as the randomisation algorithm was designed to preserve the rainflow counting results). Note, that the number of ‘occupied’ load levels for this load spectrum is lower than that for Wisper and WisperX (from 5 to 59), and that for this spectrum, the zero-stress level is 22 instead of 25. When figure 3 is compared to the results for the original Wisper spectrum shown in figure 2, it can clearly be seen that in Wisper more cycles were concentrated on a few range-mean combinations. The NewWisper2 spectrum is much more distributed over different ranges and means, implying that this load sequence is more variable amplitude in nature.

4. Experiments and Results

For the variable amplitude fatigue tests the reference laminate as used in the Upwind project was used. This is a 4 layer unidirectional glass epoxy laminate. The areal weight of the glass fabric is 963 g/m² with 95% UD fibres and 5% transverse reinforcements. The epoxy infusion resin was Hexion RIMR 135. Laminates were made by vacuum infusion in a double sided aluminium mould. The laminate thickness was set to 3 mm. The fibre volume fraction is approximately 50%.

For the fatigue tests the reference geometry as used for the Upwind test were used, rectangular specimens with 20 mm width and with a 20 mm gauge section. The nominal dimensions are shown in Figure 4. The specimens were equipped with 1 mm tabs made of FR4 grade glass-epoxy plates, with a
±45° fibre orientation. The specimens were tested in 100 kN servo-hydraulic test frames in load control mode. For each spectrum test were performed at several load levels. The spectrum sequences were repeatedly applied until failure of the specimen, where failure is defined as the inability to bear the applied load.

The experimental results are listed in table 1. The first two characters of the specimen ID refer to the laminate from which the specimen was made. The forces at the maximum peak and at the minimum valley are listed as well as the maximum stress which corresponds to the maximum force divided by cross sectional area. The number of cycles to failure is divided by the sequence length to get the total number of sequences for each test.

Looking at the results, considerable scatter is observed. For all spectra many specimens of laminate EW exhibit considerable lower fatigue life than specimens from other laminates. The cause of this difference is not known.

5. Comparison to fatigue life predictions

Fatigue life predictions for the three Wisper spectra are based on the constant amplitude fatigue data from Upwind. Predictions were generated for four CLD formulations, i.e. the Goodman diagram, a piecewise linear CLD based on $R = 10, R = -1$ and $R = 0.1$, a piecewise linear CLD based on all nine $R$ values from Upwind and the Multislope model by Boerstra. All predictions were based on simplified rainflow counting and for damage summation Palmgren-Miner was used.

In figure 5 the fatigue life predictions are plotted with the experimental data for Wisper and WisperX. In figure 6 this comparison is given for NewWisper2. For the three spectra the trend in the predictions is the same: The Goodman diagram predicts the highest fatigue life while the lowest fatigue life is obtained based on the 9 R-value CLD. The Multislope model gives predictions very close to the 9 R-value CLD and the three R-value CLD is in between.

In the evaluation of the Multislope model it must be stated that the model provides a very good fit to the Upwind data. For other datasets the model may not be able to follow the trends in the data as well, e.g. in [9] the quality of the fit of the Multislope model to the data was more varied. In such cases the quality of the variable amplitude fatigue life prediction obtained on the basis of the Multislope models is likely to be affected.

The differences between the predictions are spectrum dependent. For Wisper, Goodman predictions are a factor 30 (on a linear scale) higher than the lowest prediction. For WisperX the difference is
slightly smaller while the predictions are much closer together for NewWisper2, where a factor of approximately 7 lies between the lowest and highest prediction.

This difference can be attributed to the large number of cycles with low range and high mean that are present in the Wisper spectrum, see figure 2. As an example consider the largest dot in the figure, which corresponds to an R value of 0.5. Looking at figure 1, one can see concave CLD lines at the R-value of 0.5. Omitting the R value from the CLD formulation will move the constant life lines outward, giving more optimistic life predictions.

NewWisper2 contains more cycles with lower means and R-values between -1 and 0.1. For these R-values the differences between the various CLD formulations are much smaller and therefore the effect on the life predictions is far less pronounced.

Table 1. Results of Variable Amplitude fatigue tests

| Spectrum | Specimen ID | max. Force [kN] | min. Force [kN] | σ_max [MPa] | Cycles to failure no. of sequences |
|----------|-------------|-----------------|-----------------|-------------|----------------------------------|
| Wisper   | EO10R08     | 36.0            | -22.2           | 605         | 186018                           | 1.40                           |
|          | EW06R08     | 36.0            | -22.2           | 584         | 137188                           | 1.03                           |
|          | EO08R08     | 30.0            | -18.5           | 508         | 837205                           | 6.31                           |
|          | EO04R08     | 30.0            | -18.5           | 506         | 725339                           | 5.47                           |
|          | EW24R08     | 30.0            | -18.5           | 486         | 955433                           | 7.20                           |
|          | IV04R08     | 25.0            | -15.4           | 430         | 2535831                          | 19.11                          |
|          | EO06R08     | 25.0            | -15.4           | 425         | 3139968                          | 23.66                          |
|          | EW19R08     | 25.0            | -15.4           | 410         | 693116                           | 5.22                           |
|          | EW17R08     | 25.0            | -15.4           | 408         | 565616                           | 4.26                           |
| WisperX  | FI07R08     | 30.0            | -18.5           | 490         | 56006                            | 4.36                           |
|          | FI01R08     | 30.0            | -18.5           | 489         | 668099                           | 52.07                          |
|          | FI06R08     | 30.0            | -18.5           | 487         | 99888                            | 7.78                           |
|          | FI05R08     | 30.0            | -18.5           | 486         | 68713                            | 5.56                           |
|          | EW18R08     | 25.0            | -15.4           | 410         | 131215                           | 10.23                          |
|          | FI09R08     | 25.0            | -15.4           | 409         | 1992127                          | 155.26                         |
|          | FI11R08     | 25.0            | -15.4           | 407         | 1491852                          | 116.27                         |
|          | FI13R08     | 25.0            | -15.4           | 406         | 1015076                          | 79.11                          |
|          | FI16R08     | 25.0            | -15.4           | 405         | 657837                           | 51.27                          |
|          | EW20R08     | 25.0            | -15.4           | 405         | 323628                           | 25.22                          |
|          | EW13R08     | 25.0            | -15.4           | 401         | 412158                           | 32.12                          |
| NewWisper2| EO09R08     | 36.0            | -16.5           | 610         | 65960                            | 1.38                           |
|          | EO07R08     | 40.0            | -18.4           | 594         | 17985                            | 0.38                           |
|          | FI11R08     | 36.0            | -16.5           | 588         | 116285                           | 2.43                           |
|          | EW07R08     | 36.0            | -16.5           | 586         | 32614                            | 0.68                           |
|          | EO13R08     | 36.0            | -16.5           | 586         | 188325                           | 3.94                           |
|          | EO11R08     | 30.0            | -13.8           | 500         | 259575                           | 5.43                           |
|          | EW08R08     | 30.0            | -13.8           | 487         | 353179                           | 7.39                           |
|          | EW22R08     | 30.0            | -13.8           | 482         | 157338                           | 3.29                           |
|          | EO02R08     | 25.0            | -11.5           | 424         | 1170956                          | 24.51                          |
|          | EO05R08     | 25.0            | -11.5           | 419         | 2013925                          | 42.16                          |
|          | EW02R08     | 25.0            | -11.5           | 414         | 1943211                          | 40.68                          |
|          | IV05R08     | 20.0            | -12.3           | 345         | 15284143                         | 319.99                         |
|          | EW15R08     | 20.0            | -12.3           | 328         | 7931635                          | 166.06                         |

When comparing the predictions to the experimental data conclusions are easily drawn for NewWisper2 in figure 6. The Goodman diagram provides highly un-conservative predictions, which
confirm the findings in [1]. Experimental results are close to the lower bound of the predictions, implying that a detailed description of constant amplitude fatigue behaviour is a prerequisite for good predictions. Although many specimens exhibit slightly lower fatigue life than the predictions, the deviation is similar to the scatter that can be observed in constant amplitude fatigue tests. Therefore one can argue that these predictions are as good as can be expected because of the inherent variability in composites performance.

For Wisper and WisperX the image is more diverse. Fatigue lives of many specimens exceed the lowest predictions. Still the lowest predictions are considered to be the preferable choice as the others are non-conservative for many specimens. Nevertheless, especially for Wisper many experiments match well with the prediction based on the three R-value CLD. This could be an indication that cycles with a low range are less damaging in a variable amplitude fatigue sequence than they are in a constant amplitude fatigue test.
6. Conclusions
Several CLD formulations were compared based on their ability to predict the fatigue life of specimens under spectrum loading. Three different load spectra were used, Wisper, WisperX, and NewWisper2. Predictions based on the Goodman diagram confirm that this CLD formulation leads to un-conservative predictions for all three load spectra.

Comparison of the various predictions with experimental results shows that a more detailed CLD formulation will improve predictions. Considerable improvement is achieved by a piecewise linear CLD based on S-N curves for $R = 10$, $R = -1$ and $R = 0.1$. However, the failure of this model to match the concave sections in the CLD for the laminate used for this study still leads to un-conservative results.

A piecewise linear CLD based on 9 load ratios provides acceptable predictions for the variable amplitude fatigue test results. However, the test effort involved in obtaining such a CLD exceeds what is acceptable for design purposes in most cases. For the specific laminate used in this study the Multislope model provides a good alternative at reduced test effort.

In the study leading to these conclusions, no variations in counting method or damage accumulation rule were included. For example, any effect of load cycle order is not reflected.

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