A BENCHMARK ON LIFETIME PREDICTION OF COMPOSITE MATERIALS UNDER FATIGUE

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ABSTRACT: The present paper describes a benchmarking programme to compare different lifetime prediction methodologies. Lifetime prediction is still a complex task and the results depend on many factors. Thus, it is very important to know which factors have a decisive effect on the results. The main objective of this investigation is not to proof the validity of a certain prediction model, but to quantify the influence of each step of the prediction process on the results using different methodologies.

KEYWORDS: composite fatigue, wind turbine blades, variable amplitude, lifetime prediction, rainflow counting

LIFETIME PREDICTION IN COMPOSITE FATIGUE

Fatigue has a major meaning on the development and design of dynamically loaded structures such as wind turbine rotor blades. The knowledge of material behaviour and an appropriate fatigue characterization is necessary to build cost-efficient rotor blades. Although the majority of fatigue characterization is investigated under constant amplitude fatigue conditions, composite structures are subjected to random loads in service. Therefore available fatigue data doesn't represent exactly the loading in service because interaction effects are not concerned. For design of composite structures suitable techniques are needed to estimate the fatigue behaviour of the structure enclosing a lifetime prediction which is as accurate as possible without incorporating too much conservatism.

Since the 1970s, as use of composites in dynamically loaded structures increased, extensive research concerning random fatigue and its effects on damage development and fatigue life has been conducted. Today, many prediction models have been developed using different methodologies. The vast majority of these models is based on strength or stiffness degradation because these parameters can practically be measured. Another possibility is to measure crack density and length or size of delaminated areas requiring much effort and often not applicable in complex structures. For variable amplitude or random fatigue the capability of the models to account for load sequence or frequency effects is an important point of interest. Classically, in many models these effects are not considered and a linear damage

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accumulation is assumed. Although these models have proved their potential in the past, the development of non-linear fatigue models is getting more and more important to meet better with cost- and weight-efficient design-requirements.

Common lifetime prediction methods for variable-amplitude loading are usually based on the results of constant-amplitude test results and consist of a (Rainflow) counting procedure, the establishment of S-N curves and a constant-life diagram, followed by a damage accumulation rule. Thereby there are not only differences between lifetime prediction and lifetime measurement but also varieties among various prediction methods. Since the results are affected by each part of the whole process, it is important to know the size of effects contributed by any component. Therefore, a benchmark on lifetime prediction is performed within the 'OPTIMAT BLADES' project, a research program of the EU. The aim of this investigation is to compare some different possible prediction methods and determine the influence of each step of the whole process.

This paper provides a comparison of prediction methods and points out the influence of different methods used for Rainflow counting as well as statistical approaches for establishment of the SN-curves.

Load spectra and fatigue data

The WISPER and WISPERX load spectra are used for the investigations presented in this paper. The WISPER and WISPERX load sequences were proposed in the eighties as standard test sequences for wind turbine rotor blades. These are standardized variable amplitude test loading sequences and they consist of a mixture of load sequences recorded from different wind turbine blades. They are solely developed for comparison purposes in the fatigue evaluation of materials.

The WISPER(X) load sequence is described by a series of integers with range from 1 to 64 indicating load reversal points. Zero level is located at level 25. The sequence can be scaled (i.e. the integers can be multiplied by any constant) to obtain a desired maximum stress in the sequence. The WISPERX loading sequence is a derivative of the WISPER loading sequence, where all cycles with a load range smaller than 17 levels have been omitted, thus shortening the loading sequence from 132,711 cycles to 12,831 cycles.

The experimental test results used for the calculations were performed by the Netherlands Energy Research Foundation (ECN) and taken from the FACT database.

Rainflow counting

The cycle counting algorithm is the first step of any fatigue analysis and identifies the cycles included in a given complex load spectrum representing a random series of numerous loading conditions. The cycles are commonly characterized by mean and maximum stress or amplitude stress and mean stress.

Different methods exist to determine the cycles in the signal, such as level crossing methods, peak count methods or range counting methods. The Rainflow cycle counting method, developed simultaneously by Endo et al. [1] and de Jonge [2], is regarded as the best procedure for determining damaging events in a complex loading history. It registers closed hysteresis loops in the sequence, but frequency effects are generally not considered. In the past, various Rainflow counting methods were developed based on the principles of the original counting procedure but yielding different results.

In the WISPER(X)-tests investigated here, the load sequence is repeated until failure of the specimen. Nevertheless, it is sufficient to count the loading sequence and multiply the number of cycles with the number of occurrences of the sequence. The results should be the same as counting the complete spectrum.

The method developed by Endo et al./ de Jonge, starts and ends at an arbitrary point in the signal. This procedure does not extract all cycles directly. After detection of the last peak, the remaining sequence can still contain a series of peaks and troughs, called residual. This sequence can be counted as half cycles, if the contribution to the total damage is not to be neglected. Another algorithm, proposed by Downing [3], rearranges the loading sequence until the minimum trough or maximum peak is at the starting point ("cyclic counting"). With this procedure only full cycles are counted.

In this investigation the results of four different counting methods are evaluated:

- Method 1: Cyclic counting according to Downing
- Method 2: Non-cyclic counting according Endo, residual discarded
- Method 3: Modified non-cyclic counting according Endo,
- Method 4: Non-cyclic counting according Endo, residual counted, half cycles

The differences between cyclic and non-cyclic counting for the WISPERX loading sequence are given in Table 1. The most important difference is the existence of one load cycle with maximum possible amplitude for cyclic counting with high contribution to the total damage.

Range (Levels)	**Minimum Level**	**Cycles Non-cyclic count (of 12828)**	**Cycles Non-cyclic count - modified- (of 12831)**	**Cycles Cyclic count (of 12831)**
17	23	-	1	-
30	25	-	-	1
35	21	-	1	1
39	25	-	1	-
54	1	-	1	-
63	1	-	-	1

Table 1 Differences of various counting procedures for Spectrum WisperX

Description of S-N curves

Fatigue data is usually determined experimentally with constant-amplitude tests and expressed as a set of curves in an S-N-diagram (S-N-curves), each of them evaluated at a different R-value, the ratio between minimum and maximum stress:

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

The S-N-diagrams have *S*, the stress or strain component of fatigue load, as ordinate and the number of cycles to failure *N* as abscissa. For description of the fatigue data, a mathematical expression is needed to interpolate data points. Hereby pure mathematical models (linear regression analysis) and material-based statistical models (Whitney [4], Sendeckyj [5]) are distinguished.

The influence of various interpolation schemes underlies the properties of different physical assumptions and mathematic formulations of the SN-curves. In this investigation the results of three different methods used for the establishment of S-N curves are presented:

- Pure linear regression
- Whitney (wearout model, linear regression)
- Sendeckyj (wearout model, principle of equivalent static strength)

The pure linear regression method is characterised by its simplicity. Experimental fatigue data is fitted by a line in either lin-log scale or log-log scale and the slope of the line and value of y-axis intercept are the results. Though the parameters can be determined very easy, this model is not based on a physical fatigue model describing material behaviour.

The Whitney approach is based on the wearout model for fatigue characterization of composite materials and involves two assumptions: a classical power law representation of the S-N curve and a two-parameter Weibull distribution of time-to-failure. This can be written in the following equations:

$$N_0 = C^{-1} S^{-b} \tag{2}$$

$$R(N) = \exp\left[-\left(\frac{N}{C^{-1} S^{-b}} \right)^{a_f} \right] \tag{3}$$

where S is the stress, N is the number of cycles to failure, and b and C are material constants. In addition $R(N)$ denotes the probability of survival, N_0 is the characteristic time to failure (location parameter) and a_f the fatigue shape parameter. For determination of the S-N curve the experimental data is fitted at each stress level to a two-parameter Weibull distribution and a data pooling scheme applied to determine overall fatigue shape parameter a_f. Fitting the experimental data to a straight line (log-log scale) gives the parameters b and K, with K equal $C^{-1/b}$. The S-N curve is finally formulated by combining (2) and (3)

$$S = K\left[\left(-\ln R(N) \right)^{\frac{1}{a_f b}} \right] N^{\frac{-1}{b}} \tag{4}$$

Though the Whitney model is applicable with a low number of specimens, several stress levels with a certain amount of fatigue data are needed. The advantage of this statistical approach is the use of reliabilities and a material behaviour-based fatigue model.

The Sendeckyj approach is represented by a two-parameter Weibull distribution of equivalent static strength data. This data is obtained by transformation of experimental fatigue data using for instance the wearout model based on the following equation

$$s_e = s_a \left[\left(\frac{s_r}{s_a} \right)^{\frac{1}{S}} + (n-1)C \right]^S \tag{5}$$

where s_e, s_r, s_a, and n are the equivalent static strength, maximum applied cyclic stress, residual strength, and number of cycles. The slope of the S-N curve at long life is given by S and C characterizes the extent of the “flat” region of the curve at high stress levels. For fatigue failure, s_r=s_a, n=N, and Equation 5 reduces to

$$s_e = s_a (1 - C + CN)^S \quad (6)$$

For the equivalent static strength data a two-parameter Weibull distribution is assumed

$$P(s_e) = \exp\left[-\left(\frac{s_a}{b}\right)^a\right] \quad (7)$$

where a and $ß$ are the shape and scale parameters, respectively.

The advantage of the Sendeckyj approach is that fatigue data does not have to be evaluated at particular stress levels. Additionally, the possibility to take static test data into account increases the possibility to formulate a S-N curve representing more exactly the distribution of fatigue lives at higher stress levels. The disadvantage is that additional wearout model parameters must be evaluated from the data via an iterative algorithm which may include highly sensitive parameters.

Consideration of static properties in S-N curves

The static properties of a material in context with the fatigue curve are treated in different ways by the above mentioned three methods.

They are not content of the Whitney-method, since this approach does consider the Weibull-distribution of the cycles at a distinct load level. Thus, the distribution of the static properties does not fit into this philosophy.

Also the linear regression is not appropriate for including the static values into the evaluation. Experience has mostly shown that the extrapolation of the least square fit of the s-n-curve does not meet the mean value of the static tests. Thus, the integration of the static properties would lead to larger scatter and a different slope resulting in a wrong lifetime prediction.

In contrast, the Sendeckyj approach is able to include also the static properties, see Figure 1.

For presentation of the S-N curves, this is an advantage, since the low cycle fatigue behaviour of a material (up to about 10^3 load cycles) which is dominated by fibre breakage can be demonstrated by means of the parameter C. This does not influence significantly the slope of the S-N curve and, thus, the parameter a which is the measure of the scatter. Additionally, it allows to judge about the quality of a material. For example, for a sound UD-fibre dominated laminate, C should be lower or equal 1.

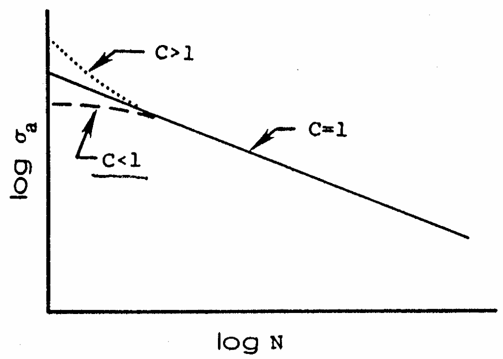

Figure 1: Shape of the S-N curve as a function of parameter C in the wearout model [Sendeckyj]

In reality, however, the design stress levels of a structure like e.g. a wind turbine rotor blade are much lower (stiffness reasons, safety factors, etc.). At those levels, the failure mechanism is dominated mainly by matrix cracking, and also the slopes of the S-N curves resulting from the different approaches are similar as shown above. Thus, for the purpose of a lifetime prediction which considers those realistic load levels it does not make very much sense to consider the static properties. Here, they can be excluded.

This may stop also discussions how static properties should be measured when presenting them in combination with a fatigue curve. There are opinions to adopt the static test speeds to the high loading rate used in fatigue tests what is in contradiction to the very low loading rates prescribed by the existing norms. At least for a lifetime prediction it plays no role.

Constant-Life Diagram

A set of S-N curves is basis for a constant-life diagram (CLD). The CLD describes the relationship between mean expected fatigue life and a loading condition, expressed as a combination of load amplitude and mean. The S-N curves are described with lines in the s_{mean}-s_{amp}-plane, connecting points with the same expected numbers of cycles to failure (constant-life line). The relationship between S-N-curve and CLD is shown in Figure 2. The points on the s_{amp}-axis are found using the constant amplitude data for R=-1. The CLD is bounded by the constant life line N=1 and the values for Ultimate Tensile Strength (UTS) and Ultimate Compressive Strength (UCS) on the s_{mean}-axis.

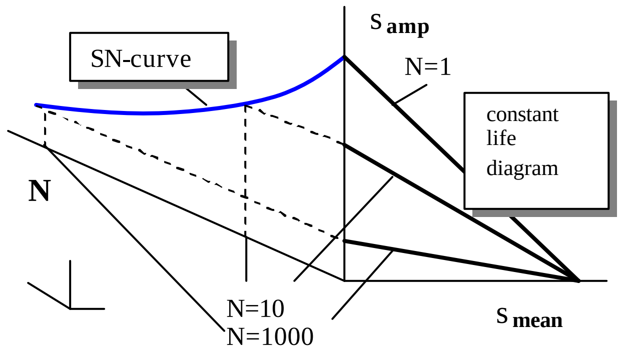

Figure 2: Relation between S-N curve and constant life diagram

Depending on the load spectrum at least three S-N curves should be used to describe the CLD. Usually these curves are determined at R-values 0.1 (Tension-Tension), -1 (Tension-Compression) and 10 (Compression-Compression) respectively. Since the establishment of three S-N curves requires extensive experimental work, sometimes one special form of the CLD, the linear Goodman diagram, is used which contains only the experimental results for R=-1 as well as UTS and UCS. But the linear Goodman interpolation is not generally valid for fiber reinforced composites. To obtain fatigue data for any R-value linear interpolation between R-values for which experimental data are available is most commonly used. The reliability of interpolated data increases by using a sufficiently fine grid of R-values. For different formulations of the CLD, see [7].

Lifetime prediction (Damage accumulation rule)

After characterization of the fatigue behaviour under constant amplitude loading conditions, a damage accumulation rule is necessary to evaluate fatigue lifetime under load spectra conditions. The traditional and most simple approach to obtain the total damage is the linear Miner summation. The contribution to the total damage for one cycle type is given by the ratio between the number of cycles in the loading history n and the expected number of cycles to failure N:

$$D = \sum \frac{n_i}{N_i} \tag{8}$$

where i denotes the cycle type, n_i the number of cycles of type i in the loading sequence and N_i the expected number of cycles to failure for type i. D is the damage number and failure expected if D reaches a value =1. Since the contribution to D of different cycle types is independent of their sequence, D does not account for any physical accumulation of damage. It cannot be asserted that D represents the fraction of total damage at any given fraction of lifetime.

After modification the Miner rule to a form incorporating three additional parameters, it can be used to predict fatigue lifetime closely correlating with experimental data.

$$D = \sum \left[A\frac{n_i}{N_i} + B\left(\frac{n_i}{N_i}\right)^C \right] \tag{9}$$

This model was proposed by Owen and Howe [9] and is sometimes referred as "Relative Miner" rule. The parameters A, B and C are determined by fitting the resulting lifetime predictions to an experimental trend line. Obviously, this experimental data has to be determined under load spectrum conditions. Thus, this rule requires additional experimental work and is not generally valid for any load spectrum.

BENCHMARK RESULTS

Since the influence of the different components of the lifetime prediction process on the results is basically identical for both load spectrums, only the results for the WISPERX spectrum are shown.

Influence of Rainflow counting

In Figure 3 the results of lifetime prediction for the different Rainflow counting procedures are given: The results of lifetime prediction for the cyclic counted sequence, referred as Method 1, are taken as reference.

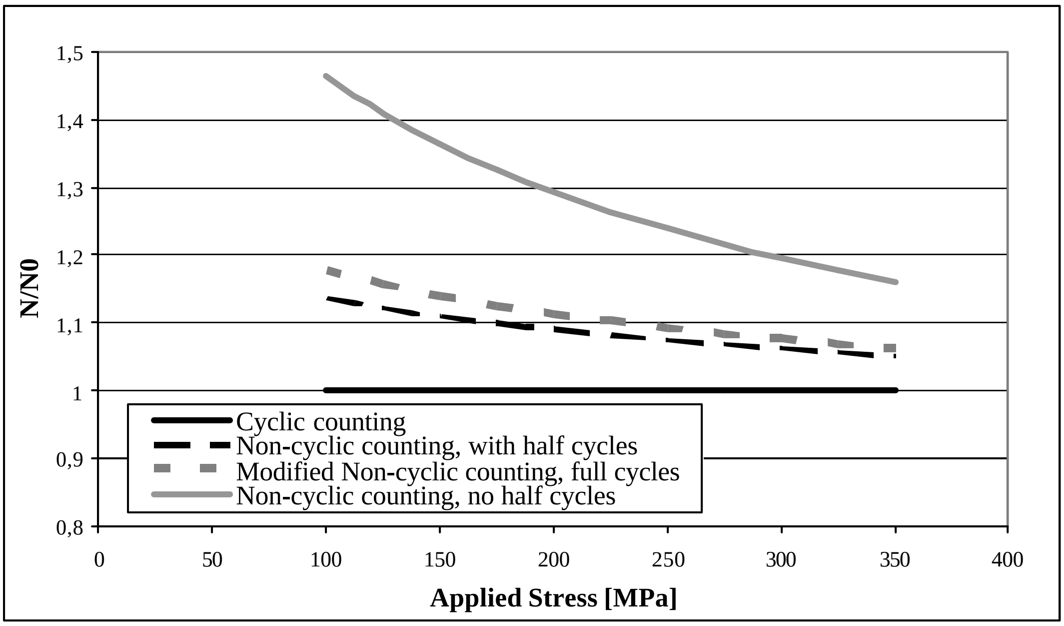

Figure 3: Results of lifetime prediction for different Rainflow counting methods

Obviously the predicted lifetime of the non-cyclic counted sequences is higher as a result from less damaging cycle-types (compare Table 1). Since the loading sequence is repeated many times for lower stress levels, the influence of the highly damaging events on the results is more severe. It must be pointed out that the lifetime predicted by the non-cyclic counting methods is up to 14%, 18% and 46% respectively higher for the given stress levels.

Therefore it has to be clearly stated which method is used because the results are considerably influenced. Lifetime prediction results given in literature have to be carefully compared with own results as well.

Influence of S-N-curves

Nearly all cycles of the WISPER(X) spectrum have positive s_{mean}-stress. So only two S-N curves have to be concerned, namely R=0.1 and R=-1 respectively.

The three different S-N curves for R=-1 are presented in Figure 4.

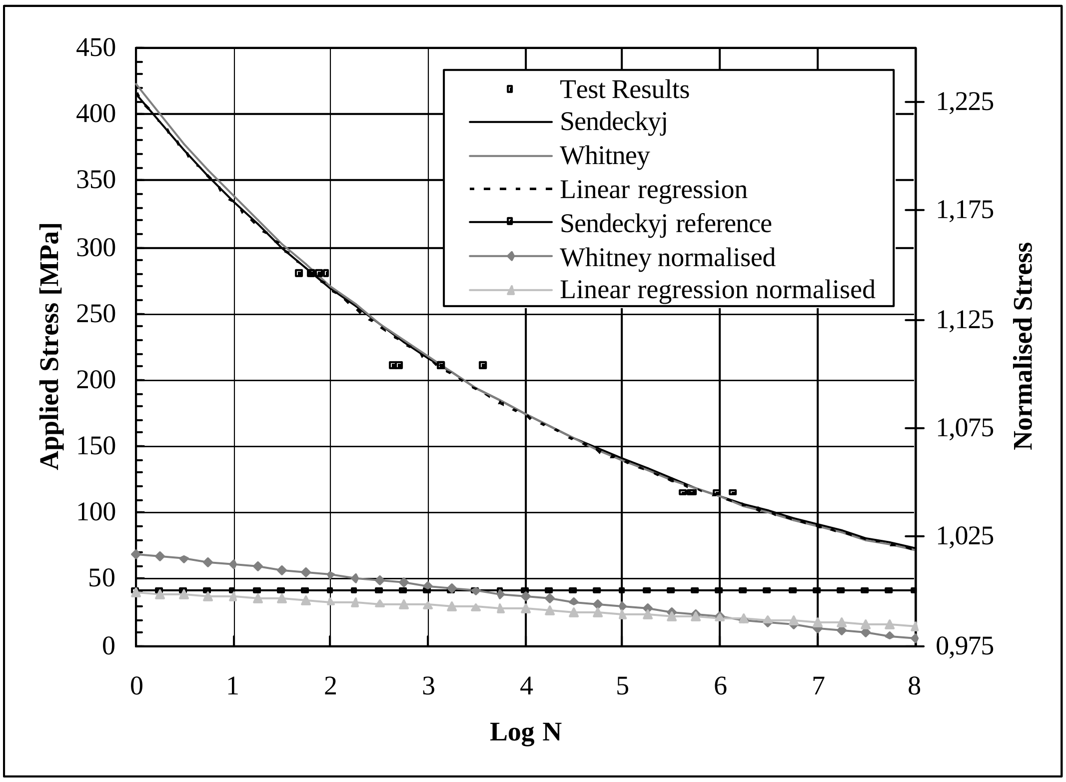

Figure 4 Comparison of S-N curves for different statistical methods (R=-1)

The deviations are very small and basically located in the regions of very high and low stress levels. As it can be seen from the normalisation with the results of the Sendeckyj method, the differences are below 2.5%. The results for the S-N curve at R=0.1 are similar (Figure 5). Deviations again exist for high as well as low stress levels but are below 5.0%.

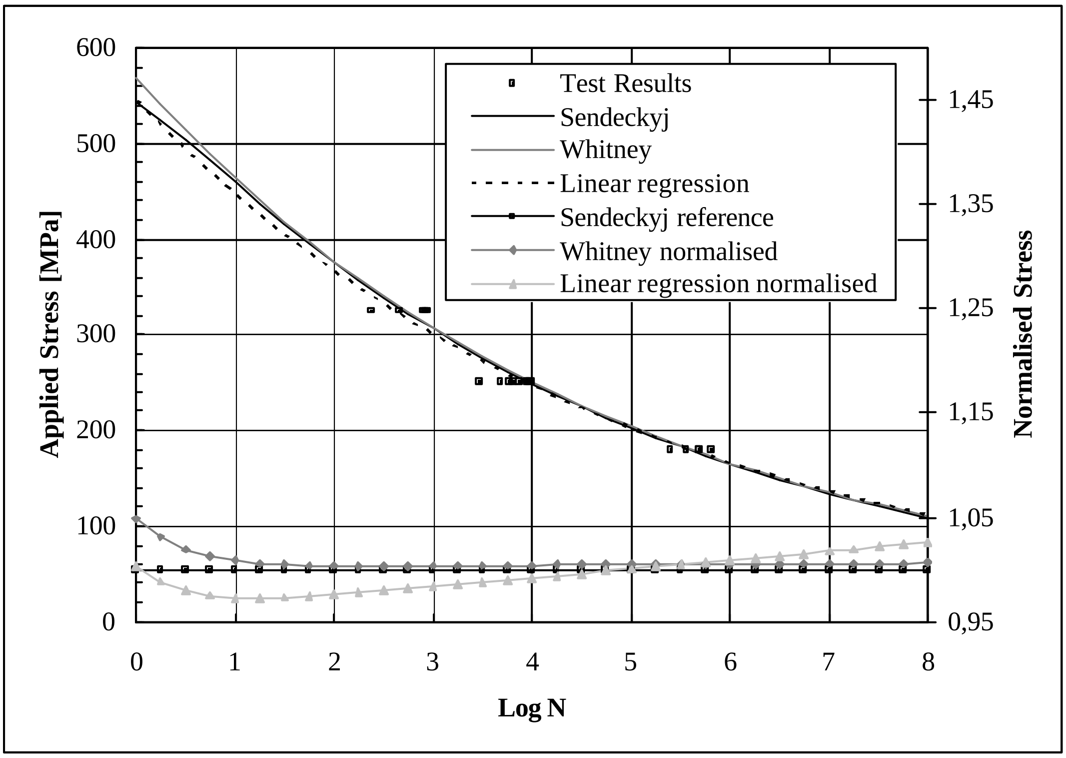

Figure 5 Comparison of S-N curves for different statistical methods (R=0,1)

In contrast to the large differences of the lifetime predictions detected for the various counting results, the influence of the different statistical methods on the predicted lifetime is smaller, see Figure 6.

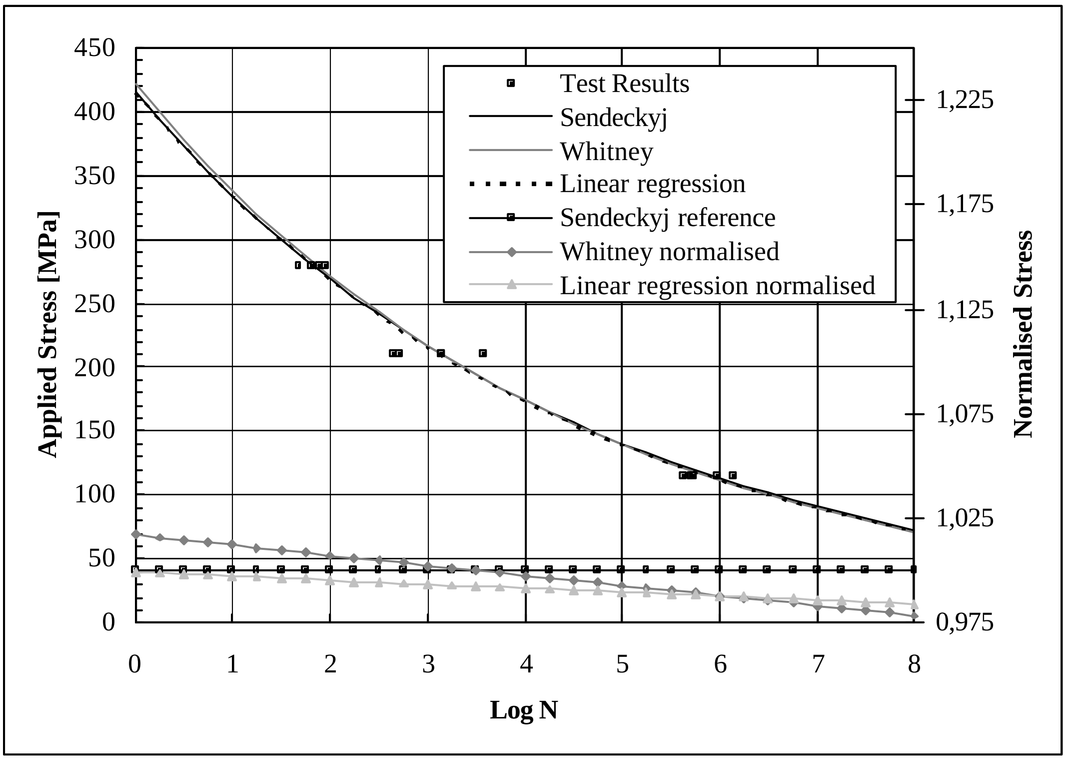

Figure 6: Results of lifetime prediction for different statistical methods

The differences for the lifetime prediction results are located at low and high stress levels, according to the deviations of the single S-N curves (see Figs. 3and 4). The differences in the high cycle regime may be reduced if corresponding test results for establishment of the S-N curves are used.

Influence of Constant-Life Diagram

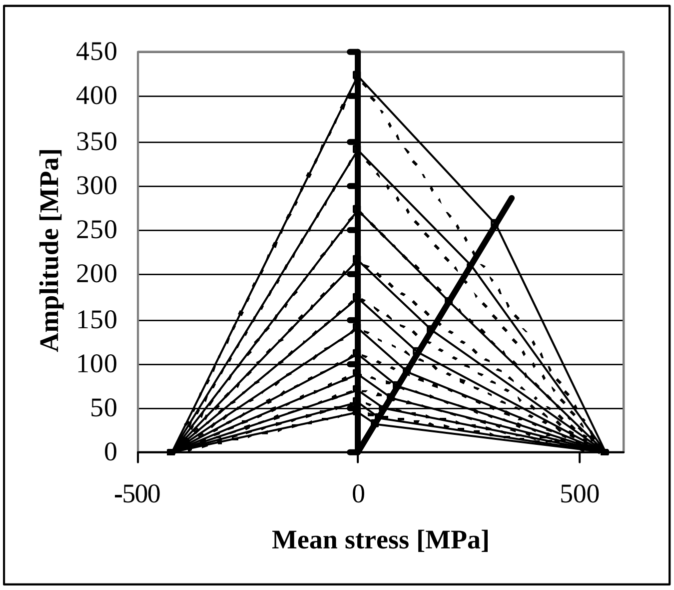

Figure 7: Differences in CLD-Diagrams

As mentioned in the section about the constant-life diagram, the quantity of used S-N curves and the type of interpolation between these different S-N curves has an decisive effect on the results of the lifetime prediction. Figure 7 shows the CLD for 2 S-N curves (solid line), namely R=-1 and R=0.1. On the positive stress-axis additionally the Goodman diagram is shown, if the S-N curve having R-Ratio equal 0.1 is dropped (dashed line). Obviously, the differences in the CLD are enormous.

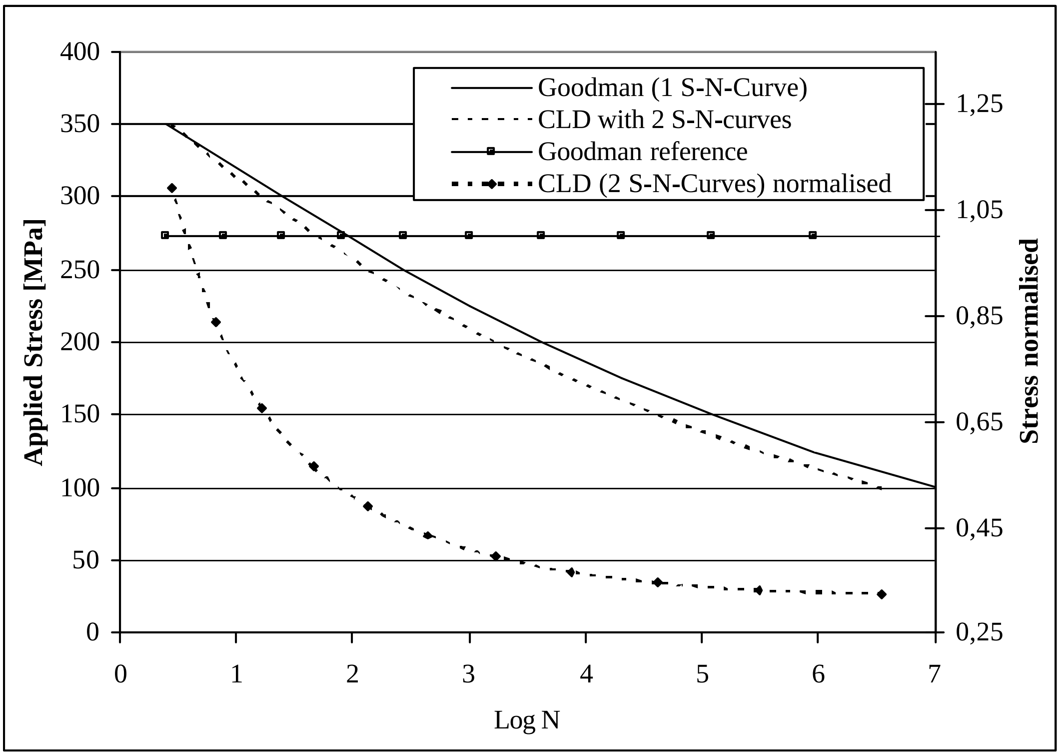

Figure 8: Influence of CLD on lifetime prediction results

As it can be seen from Figure 8, the predicted lifetime for the CLD using 2 S-N curves is only one third of the estimated value derived from the Goodman diagram. Thus, the prediction gets more conservative. In general, this tendency is maintained if further S-N-curves are added to the CLD, but the differences will reduce.

SUMMARY

A benchmark on different lifetime prediction methodologies was performed with the main objective to identify the size of influence which is contributed by each part of the prediction process to the total results. The most severe influence is given by the Rainflow counting algorithm and the constant-life diagram. These process-steps can increase or reduce the predicted lifetime decisively and can affect the results more than the application of a different physical model. Thus, it has to be clearly stated which algorithms or methods are used for the prediction. Furthermore, careful attention has to be paid for comparison of own results with others given in literature.

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