ORAL/POSTER REFERENCE: ICF100717PR

A Method for Variable Amplitude Lifetime Calculation in the High Cycle Regime

H. Zenner and S. Pöting

Institute for Plant Engineering and Fatigue Analysis
Technical University of Clausthal
Germany

Abstract

Lifetime predictions for components in the high cycle regime are still inadequate. A main reason for the inadequacy is the insufficient knowledge about the failure mechanisms and the lack of a simulation model.

Two different failure mechanisms have been reported in independent papers at the Euromech Conference from 1998 in Paris. The observed failures have been located on the surface and underneath the surface of specimens in a single test series. A simulation model describing these effects is not jet known. Other observations are suggesting a stepwise decreasing S-N-curve for constant amplitudes. None of the well-known modifications of the Miner-Rule are taking these effects into account.

An analysis of a wide database of variable amplitude tests on components leads to the conclusion that none of the Miner-Rule Modifications is capable to describe all test results. Another method to calculate the lifetime of components under variable amplitude loadings was introduced. This method is used to describe S-N-curves of components for variable amplitudes using a parameter to adjust the curve fit.

Therefore an investigation based on published data of variable amplitude fatigue tests has been made. A phenomenological description for variable amplitude test S-N-Curves has been evaluated on its accuracy to describe the test results.

Keywords

high cycle fatigue, lifetime prediction, lifetime calculation, variable amplitude test, spectrum loading

Introduction

Multiple components are used in structures and machines such as vehicles, offshore structures, as well as railway components and engines for more than 8 to 10 years. During their utilisation these components are exposed to 10^9 and more load cycles. In the high cycle regime failures of components have occurred even though the peak loads of the component's spectrum loading are just fairly above the fatigue limit. Even though components designed by the fatigue limit exposed to a few single overloads can fail in this regime. This leads to the question: Is there a fatigue limit and how can a lifetime prediction for variable amplitude loaded components be calculated more accurate in the high cycle regime?

For the lifetime designs there are two possible ways of strength verification: calculations and experiments. The experimental strength verification in the very high cycle regime is only in a few possible cases due to the long experiment time and high costs of testing. Due to these reasons there is only a limited number of test results available for the high cycle regime and experiments must carefully be monitored to gain the most possible information.

The lifetime calculation verification is based on various lifetime calculation models and modifications. Nevertheless, the calculated lifetimes are varying up to a factor of 200 in lifetime for spectrum loads with maximum stresses just above the fatigue limit. Therefore for spectrum loading is a high uncertainty in the predicted lifetime of a component.

Lifetime Calculation for Variable Amplitude

Constant Amplitude Component Stress Analysis

Lifetime prediction of components is based on stress analysis. These analyses are either base on nominal stress analysis, local stress analysis. In more complicated cases of complex components the finite element method (FEM) is used to determine the local stress distributions and to find the most claimed section of the component. A component, which shows no stress concentration, is considered a well-designed component because all sections of the component are equally stressed. The spots of stress maximums are called critical spots. These spots are considered the weakest spots of the design where the component is expected to fail.

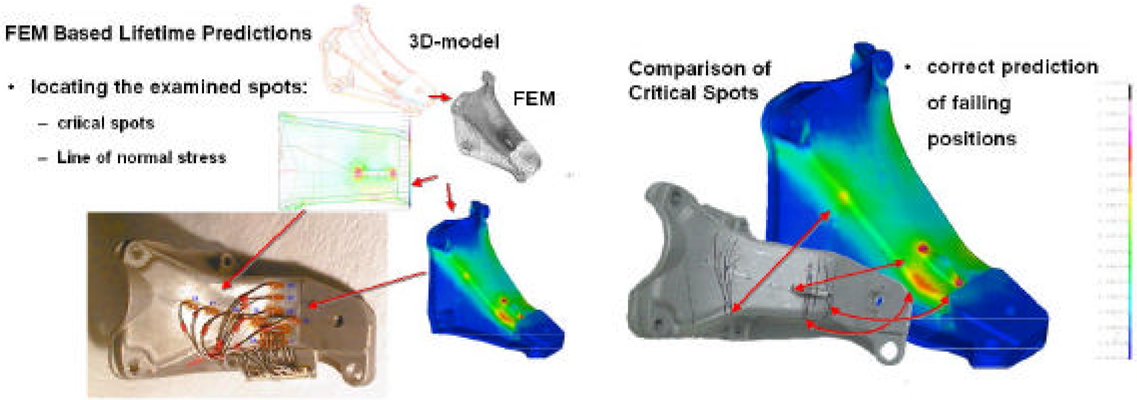


Figure 1: Elastic-Plastic Stress Analysis Compared to Strain Gauge Measurements

The FEM-analysis of such stress distribution can be verified using strain gauges to analyse local strains and calculate elastic stresses. These stresses can be compared with the analytical calculated local stresses on these spots. The accuracy of a FEM-model can be evaluated by a comparison of the calculated stresses by FEM analysis to the observed experimental stresses for elastic deformations.

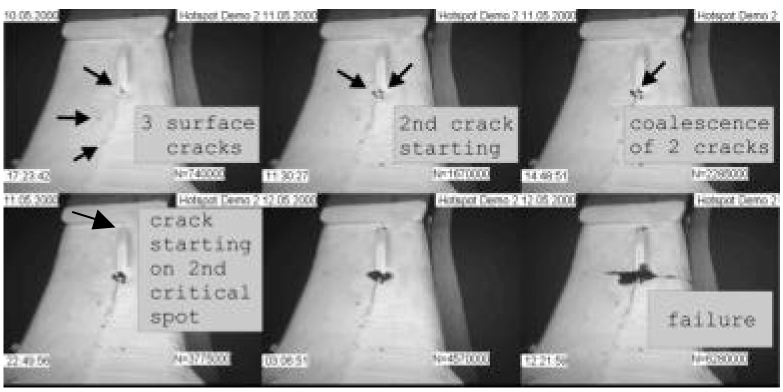


Figure 2: Digital Video Test Observations of Multiple Surface Cracks

Based on the applied load the local stress or the nominal stress can be calculated. Compared with maximum applicable stress a lifetime prediction can be made for constant amplitude test. For constant amplitude test the lifetime calculations are quite satisfactory. They are based on S-N-curves of constant amplitude test with the same material properties as specimen properties such as load ratio, surface structure, material texture, e.g.. In case these S-N-curves do not exist the influences can be described by factors [2].

Variable Load Analysis

Machine parts today are subjected to variable amplitude loads during their lifetime. Long time load spectrum analysis of these components can be used to determine the frequency distribution of amplitude loads as well as a history of load amplitudes applied to the component during its life cycle.

In cases when a load history or a load spectrum of a component is not available generalised load spectrum can be used for experimental analysis. Standardised load spectra are commonly used for variable amplitude tests if it is not a specific load history for a component, which is tested [9]. A load history is the normalised load spectrum following a normal distribution. Another load history is a normalised straight-line load spectrum distribution. For aircrafts or rolling-mill components special standardised load spectrum histories like TWIST or WASA have been established.

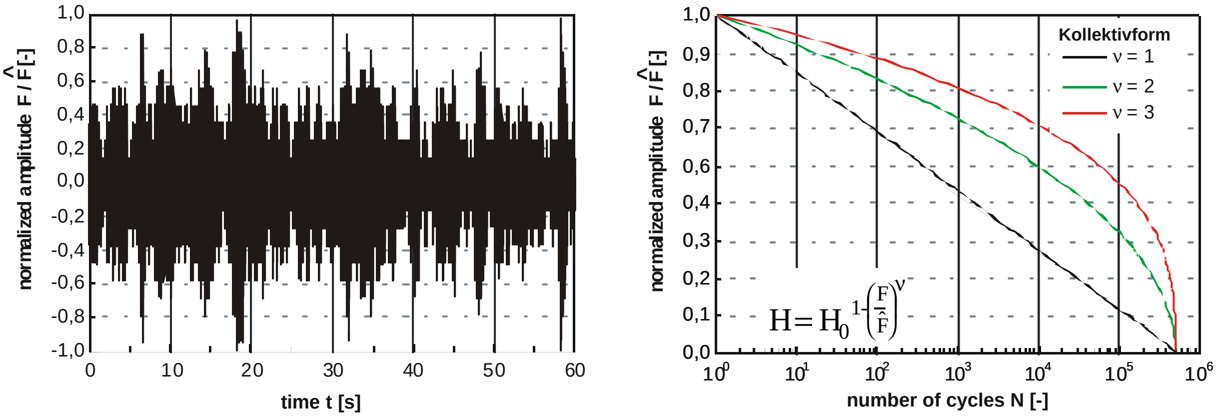


Figure 3: Loading Amplitude Time Plot and Frequency Spectra

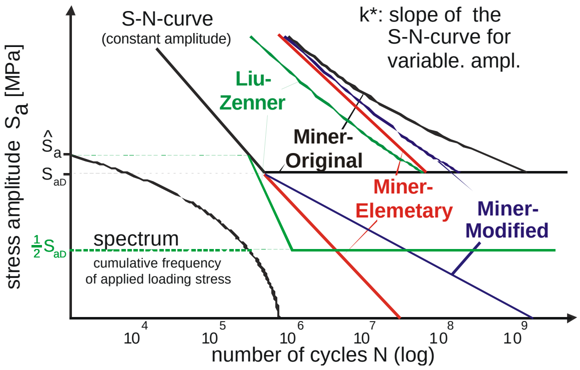
It has been noticed that spectrum loads inducing stresses just below or above the fatigue limit can lead to component failures even though mostly subjected stresses are below the fatigue limit. Therefore the question is how do these loads attribute to the failure of such components and how can it be calculated?

Variable Amplitude lifetime Prediction

The linear damage accumulation is commonly used to calculate a cumulative damage sum using Miner's Rule and its modifications. For the original Miner's Rule is assumed that each load cycle has an average according to the description the slope of the S-N-curve for variable amplitudes [5, 6, 7, 11]. The linear damage accumulation assumes that each load at a certain level attributes a damage to the component, eqn. (1). Further more it is assumed that all cycles are contributing to the components damage equally and therefore the damage sum can be calculated by the sum of the damages of all cycles and failure occurs when the damage sum equals one [6].

$$D = \sum_{i=1}^{N} d_i \qquad d_i = h_i \cdot \frac{1}{N_i} \tag{1}$$

D: damage sum
d_i: damage sum of a
N_i: number of cycles to failure at a constant stress amplitude level i
h_i: number of cycles at a stress amplitude i



	S_a ³ S_D	$S_a < S_D$
original:	$k^* = k$	$k^* = \infty$
elementary:	$k^* = k$	$k^* = k$
modified by Haibach:	$k^* = k$	$k^* = 2\,k - 1$
modified by Liu/Zenner:	$k^* = (k + m) / 2$	$k^* = \infty$

k: slope of the S-N-curve for constant amplitude
m: slope of the crack growth S-N-curve for constant amplitude

Figure 4: Lifetime Predictions Using Miner Modifications

Current data analysis of variable amplitude tests has shown that components tend to fail at a mean value damage sum equal 0,3 for steel and 0,5 for aluminium [3, 4, 8, 11]. Therefore the relative Miner's Rule is introduced. Based on variable amplitude tests of components a different damage sum can be used to calculate the failure of a component. The analysis of the Miner' Rule and its modifications has proven that the modification by Liu/Zenner has the most accuracy. The different Miner's Rule modifications lead to longer or shorter calculated lifetimes [7].

Lifetime Predictions for Variable Amplitude Loads in the High Cycle Regime
In the high cycle regime the calculated lifetimes of variable amplitude tests differ magnificently for the different Miner's Rule modifications. The calculated lifetimes can differ depending on the spectrum, the slope k of the S-N-curve and the components up to a factor of 200 in lifetime. The modification leading to the shortest calculated lifetime is the Miner Modification by Liu/Zenner. The modification leading to the longest calculated lifetime is the Miner original modification. Compared to the experimentally investigated lifetimes the Miner elementary modification tends to lead to a safe and conservative lifetime calculation, the Miner original modification tends to lead to an unsafe and progressive lifetime calculation. For the experimental test results it was observed that the experimental lifetimes are in the range of the calculated lifetimes of the Miner elementary and original modification.

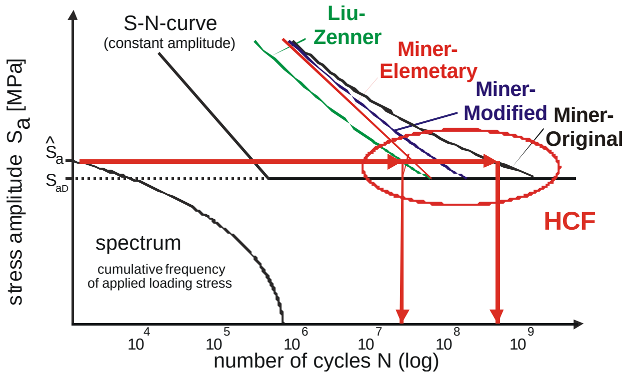


Figure 5: Difference in calculated lifetimes depending on Miner Modifications

Lifetime Prediction using a Form Parameter c
A method to describe a S-N-curve for variable amplitudes was published by [1]. The function describes any S-N-curve for variable amplitude tests in dependency of a single form parameter, eqn. (2). This function uses the point of the fatigue limit of the S-N-curve for constant amplitude loads as a reference point. The base point for the calculation is the limiting number of load cycles to the fatigue limit and the fatigue limit of the S-N-curve for constant amplitudes. The number of load cycles which can be applied to a component under variable amplitude loads of a spectrum with a maximum load $\hat{S}$ can be calculated by the use of the fatigue limit base point for constant amplitudes. The function for the finite life fatigue strength of constant

amplitude S-N-curves is used with a modified slope k^*. The modification of the slope k^* depends on the interval of the maximum spectrum load and the constant amplitude fatigue limit described by the form parameter c.

$$N = N_D \cdot \left(\frac{S_D}{\hat{S}} \right)^{k^*} \qquad k^* = k \cdot \left[1 + \frac{c}{\hat{S}/S_D - 1} \right] \tag{2}$$

S_D: constant amplitude fatigue limit
k: slope of constant amplitude S-N-curve
$\hat{S}$: spectrum maximum applied stress
c: form parameter

Setting the parameter to its extreme values the function describes the calculated lifetime curve of variable amplitude tests calculated by using the elementary or original Miner's Rule. The influence of the spectrum length and the spectrum load distribution can be described by this function. The experimentally observed effect of a lifetime reduction in case of a load spectrum with a greater number of higher loads can be described as well as the effect spectrum length.

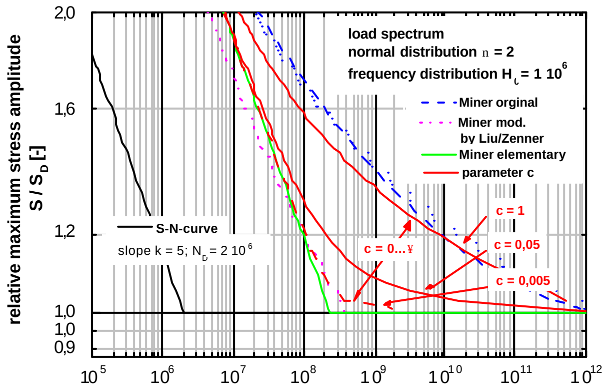


Figure 6: Capabilities of the Form Parameter c to Describe Variable Amplitude Lifetimes

From the analysis of the published data [8] of variable amplitude tests tendencies for the parameter c can be concluded. The results of the quantitative analysis are shown in table 1.

TABLE 1
INFLUENCE ON THE FORM PARAMETER C

influence factors	parameter indication	form parameter c
notch factor: K_t	high	↑
	low	↓
irregularity: I [11]	1	↓
	0	↑
stress ratio: R	-1	↑
	0	↓
slope of S-N-curve: k	steap	↓
	even	↑

This analysis leads to the following proposal of a function calculating the form parameter c in dependency of the above influence factors, eqn. (3).

$$c = f\left(K_t, I, R, k\right) \qquad (3)$$

Conclusions

This newly introduced function for variable amplitude lifetime prediction provides an easy method for a more accurate lifetime prediction. Based on constant amplitude tests and load analysis lifetime predictions can be made. More precise lifetime predictions can be made even for the high cycle regime.

Acknowledgements

Funding for the research project was provided by work community of industrial research union “AiF - Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e.V., Köln“, the German Union for Welding and Related Processes “DVS - Deutscher Verband für Schweißen und verwandte Verfahren e. V., Düsseldorf “ and the Research Union Propulsion Techniques “FVA – Forschungsgemeinschaft Antriebstechnik e.V., Frankfurt“. Further support was provided by: VW – Volkswagen AG, Braunschweig; Corus Aluminium Technique, Bonn; Alstom LHB, Braunschweig; ADTranz, Berlin; DUEWAG, Duisburg.

References

1. Schütz, W; J. Bergmann; M. Hück (1988). *Gemeinschaftsarbeit Pkw-Industrie / IABG Relative Miner-Regel.* Technische Berichte TF–2022, Industrieanlagen-Betriebsgesellschaft mbH, Germany
2. Gudehus, H.; Zenner, H. (1995). *Leitfaden für eine Betriebsfestigkeitsrechnung.* ISBN 3-514-00445-5, Verein Deutscher Eisenhüttenleute, Düsseldorf, Germany
3. Eulitz, K.-G.; Döcke, H.; Esderts, A. (1994). *Lebensdauervorhersage I.* Forschungsheft 184, Jahrgang 1994, Forschungskuratorium Maschinenbau e.V., Frankfurt, Germany
4. Eulitz, K.-G.; Kotte, K. L.; Zenner, H. (1997). *Lebensdauervorhersage II*, Forschungsheft 227, Jahrgang 1997, Forschungskuratorium Maschinenbau e.V., Frankfurt, Germany
5. Miner, M. A. (1945). *Cumulative Damage in Fatigue*. ASME Journal of Applied Mechanics, Vol. 12, pp. 159 – 164, USA
6. Schütz, W.; Zenner, H. (1973). *Schadensakkumulationshypothesen zur Lebensdauervorhersage bei schwingender Beanspruchung.* Werkstofftechnik, book 1 and 2, pp. 25-33 and 97-102, Germany
7. Schütz, W.; Heuler, P. (2000). *Miner’s Rule Revisited*. Materialprüfung Nr. 6, pp.245 – 251, Carl Hanser Verlag, Munich, Germany
8. Eulitz, K.-G.; Kotte, K. L. (1999). *Datensammlung Betriebsfestigkeit Teil 1 und Teil 2*. ISBN 3-8163-0383-8, VDMA Verlag GmbH, 1999, Frankfurt, Germany
9. Brune, M.; Eifler, D.; Heuler, P.; Schütz, D.; Schütz, W.; Ungerer, W.; Zenner, H. (1990). *Standardisierung von Lastfolgen und Verbesserung der Lebensdauervorhersage für Bauteile in Walzwerksantrieben*. VBFEh-Bericht Nr. 40, Vereins zur Betriebsfestigkeitsforschung, Düsseldorf
10. Zenner, H. (1997). *Lebensdauerberechnungskonzepte: Beschreibung – Kritik – Entwicklung*. DVM-Bericht Nr. 800, Deutscher Verband für Materialforschung und –prüfung e.V., Berlin, Germany
11. Haibach, E. (1989). *Betriebsfestigkeit – Verfahren und Daten zur Bauteilberechnung.* VDI-Verlag GmbH, Düsseldorf, Germany