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Fatigue life prediction based on variable amplitude tests—specific applications

Thomas Svensson[a], Pär Johannesson[a,*], Jacques de Maré[a,b]

[a]Fraunhofer Chalmers Research Centre for Industrial Mathematics, Chalmers Science Park, SE 412 88 Göteborg, Sweden
[b]Mathematical Statistics, Chalmers University of Technology, SE 412 96 Göteborg, Sweden

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Abstract

Three engineering components have been tested with both constant amplitude loading and with different load spectra and the results are analysed by means of a new evaluation method. The method relies on the Palmgren-Miner hypothesis, but offers the opportunity to approve the hypothesis validity by narrowing the domain of its application in accordance with a specific situation. In the first case automotive spot weld components are tested with two different synthetic spectra and the result is extrapolated to new service spectra. In the second case, the fatigue properties of a rock drill component are analysed both by constant amplitude tests and by spectrum tests and the two reference test sets are compared. In the third case, butt welded mild steel is analysed with respect to different load level crossing properties and different irregularity factors.

Keywords: Cumulative fatigue; Confidence limits; Life prediction; Model errors

1. Introduction

Fatigue life assessment in industrial applications involve a lot of sources of uncertainty such as material strength, notch geometries, defect contents and residual stresses. Often, these uncertainties are substantial enough to prevent detailed analysis of the fatigue phenomenon as such, and thereby, force the designer to base the assessment on the global behaviour of the component in question, i.e. from an experimental Wöhler curve.

When components are subjected to variable amplitude service loads, additional uncertainties arise; how is the loading in laboratory tests related to the loads that could be expected to appear in service? Traditionally this problem is solved by using the simplifying assumption of damage accumulation, and constant amplitude tests in laboratory are transformed to variable amplitude severity by the Palmgren-Miner rule

$$D = \sum_{i=1}^{m} \frac{n_i}{N_i}$$

which says that a load cycle with amplitude S_i adds to the cumulative damage D, a quantity $(1/N_i)$. Here, N_i denotes the fatigue life under constant amplitude loading with amplitude S_i and n_i is the number of load cycles at this amplitude. The lack of validity of this accumulation rule has been demonstrated in many applications and in consequence its usage will introduce uncertainties which must be compensated for by safety factors, see for instance [1–4].

One possible way to diminish the deviations from the damage accumulation rule is to perform the laboratory experiments closer to the service behaviour with respect to the loads. A method for establishing a Wöhler curve based on variable amplitude loads has recently been developed and is presented in a parallel paper [5].

The use of this method should be customised to each specific application by performing laboratory tests with load spectra covering different service requirements. One idea is that service measurements are used to establish a few reference load spectra for use in laboratory tests. Based on the resulting variable amplitude Wöhler curve, fatigue

* Corresponding author. Tel.: +31 772 4295; fax: +31 772 4260.
E-mail address: par.johannesson@fcc.chalmers.se (P. Johannesson).

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life can be predicted for load spectra similar to the reference types.

Three different components, each with a specific set of load spectra, were investigated. (1) Spot welded components from an automotive application were subjected to spectra of different types, two synthetic spectra and one from an automotive proving ground. (2) Suspension arms from rock drilling machines were subjected to a large number of load spectra with varying irregularity and mean values, all created from field measurements. (3) Welded specimens of mild steel were subjected to four different load spectra, created in the purpose of studying the effect of irregularity and spectrum type.

All three applications were investigated with respect to the new method for establishing a variable amplitude Wöhler curve. Fatigue life tests were performed and the new method was compared to damage accumulation assessment based on constant amplitude tests. It was found that the prediction errors diminish when constant amplitude reference curves are replaced by curves based on reference spectra. In addition, the influences of irregularity, mean values, and spectrum type are discussed.

2. Estimating material fatigue properties from variable amplitude tests

The traditional Palmgren-Miner method is adjusted here for more accurate life predictions. The theory is evaluated in a parallel paper [5] and is summarized here: The variable amplitude load is described as a spectrum of load amplitudes, calculated by for instance Rain Flow Count and discretized into m load amplitudes S_i with corresponding relative frequency of occurrence, ν_i:

$$\{(\nu_i, S_i);\quad i = 1, 2, \ldots, m\}. \tag{1}$$

The Wöhler curve is described in the form

$$N = \alpha \cdot S_{\mathrm{eq}}^{-\beta}$$

where α and β are material parameters and S_{eq} is the damage equivalent load amplitude for the actual load spectrum defined as

$$S_{\mathrm{eq}} = \left[\sum_{i=1}^{m} \nu_i S_i^{\beta}\right]^{1/\beta}.$$

The corresponding statistical model for the fatigue test is

$$\ln N_j = \ln \alpha - \beta \ln S_{\mathrm{eq},j} + \varepsilon_j, \quad j = 1, 2, \ldots, n \tag{2}$$

where n specimens have been tested, each at the equivalent load amplitude $S_{\mathrm{eq},j}$ resulting in the fatigue life N_j. The randomness due to the specimen strength is described by the independent additive random variables ε_j, each assumed to follow the Gaussian distribution

$$\varepsilon_j \sim N(0, \sigma^2), \quad j = 1, 2, \ldots, n.$$

The primary aim of the laboratory test is to estimate the material parameters α and β, which is straightforward in the case of constant amplitude tests. However, model (2) is nonlinear in the parameter β since the equivalent load $S_{\mathrm{eq},j}$ depends on β. This complication is solved in [5] by using the maximum-likelihood method. From each experiment, we can then find the estimated parameters, denoted $\hat{\alpha}$ and $\hat{\beta}$ from any set of spectrum tests.

This method thereby estimates parameters for a certain set of spectrum test results, and the choice of reference spectra and the amount of extrapolation in a specific application can be chosen with respect to engineering judgements.

3. Statistical evaluation of test results

The results from the new estimation procedure can be evaluated in detail using standard statistical tools. Except the parameter estimates, one also obtains an estimate of the variance of the random property ε; $\hat{\mathrm{Var}}[\varepsilon] = s^2$, and uncertainties in parameters, estimated lives, and predicted lives can be evaluated. In particular, prediction intervals can be calculated for a single spectrum prediction or for a group of predictions giving the possibility to judge if there are systematic deviations from the damage accumulation rule or if the deviation may be a result of randomness.

Here, we will study mainly two questions about the cumulative damage results. The first is an extension of the usual question: Can fatigue life be predicted for a spectrum result if the material properties are estimated from constant amplitude tests? Here, this question can be extended thus: Can fatigue life be predicted for a certain spectrum result if the material properties are estimated from other spectra, and how close should the reference spectra be to the prediction situation?

A second question is sometimes raised in view of spectrum fatigue test results: is the exponent β different for different types of spectra or can it be regarded as a pure component property?

The first question can be studied with the following property

$$N_{\mathrm{rel}} = \frac{N_{\mathrm{f}}}{N_{\mathrm{pred}}}, \tag{3}$$

i.e. the relative life described as the experimental life N_f compared to the predicted life, N_{pred}. By the methodology developed in [5], one can calculate prediction limits for this property, either for a single prediction or for the geometric mean of several predictions. If such prediction limits cover unity, the Palmgren-Miner rule cannot be rejected, but the mean deviation may be explained by random behaviour. Throughout this paper we will use 95% confidence and prediction limits, which means that if the test procedure