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Fatigue life assessment for large components based on rainflow counted local strains using the damage domain

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ABSTRACT

The present paper deals with the fatigue life assessment of the large components which are common in heavy plant engineering. A calculation model was developed to estimate the degree of utilisation of structural components based on rainflow counted local strains measured on machines during industrial use. A local approach was followed, but not in the classical cycle by cycle definition, since this information is generally not available from the measurements. For calculation, the rainflow data is transformed element-wise into the damage domain using the damage parameter as defined by Bergmann. The calculation model was calibrated for the ductile iron EN-GJS-400-15U by strain controlled constant and variable amplitude fatigue tests with lives that extended into the high cycle domain. Furthermore, the calculation model was validated by a strain controlled variable amplitude control test. The variable amplitude tests are based on measured rainflow data. For preparation, a method of omitting load cycles from the primary data that had a negligible damage contribution prior to load sequence reconstruction was developed. The sensitivity of the material to mean stress was considered in the process by utilising the damage domain.

The comparison of calculated results using the calibrated calculation model with experimental results from the control test shows a satisfactory match when using a constant characteristic damage sum as a failure criterion. The accuracy of the computation can be increased by considering the damage potential of the load spectra.

1. Introduction

In heavy plant engineering, the dimensioning of machine components is determined by the large sizes and small build quantities of the utilised machinery, making an approach based on prototypes impractical.

A typical example of heavy plant engineering is the design of equipment used in the cement industry. The challenges in the dimensioning of this machinery are typically met by using a computational approach. Accordingly, the initial designs of the components are solely based on calculations, commonly using the finite element method. The results of the calculations are assessed by using a local approach.

Verification of this practice is achieved by monitoring machines in industrial use. With regard to the local approach, verification is conducted by gauging local strains at design relevant hot spots. This monitoring can last for several years, thus making characteristic load spectra well known. The large amounts of data make the continuous storage of load sequences impossible. Thus, load histories are commonly captured using rainflow counting. To date, no optimised method has been available to use the complete information from the rainflow counted data to assess the utilisation of the monitored machinery. In principle, an instrument at the current state of technology is available via the FKM-guideline [1], but distinctive load spectra have frequently such low damage potential that the validity limit of the guideline is commonly reached. Furthermore, the large components, especially structures made from ductile iron, are prone to imperfections and variation of the local material properties, which cannot be considered using the guideline.

In this paper, a calculation model is presented, which allows the estimation of actual local utilisations, solely based on rainflow counted data. Input parameters are the cyclic stress–strain curve, the strain *S–N* curve and the load history in the form of a rainflow matrix. In contrast to the conventional local approach and taking into account industrial practice, damage assessment is not conducted as a cycle by cycle analysis, but, for each respective element of the rainflow matrix in the damage domain, by using the damage

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parameter as defined by Bergmann [2]. The calculation model is modular, allowing the consideration of local deviations of material properties.

This paper is composed of three parts: In the first part, a typical load spectrum measured on a vertical roller mill, of a type widely used in the cement industry, is presented in order to emphasise the motivation for the given task. In the second part, the developed calculation model is introduced and, finally, experimental verification for the ductile iron EN-GJS-400-15U is shown.

2. Service loads

In general, the industrial use of the plants chosen for measurement has priority over the data collection process. Test runs, e.g. to collect data on distinctive modes of operation, usually cannot be performed. In order to obtain representative data, measurement systems are typically set up to work over long periods of time – several months or even years. These long time spans of data acquisition make a manual monitoring of the plant operation and, when indicated, a hand-triggered data collection impossible. Accordingly, measurement systems are rigged to work continuously whenever the plant is in operation. However, the continuous data collection makes the storage of strain signals in the time domain impractical. Consequently, the data is reduced to its damage information using online rainflow counting.

A typical example of a measurement result is shown in Fig. 1a. The depicted rainflow matrix of local strains was collected on a vertical roller mill over a period of approximately two years and accounts for 287 days of operational use, meaning that a significant amount of the intended operational life was monitored. Consequently, the strain history and the representative strain spectra of a critical point are known with a very high certainty. To further illustrate a typical fatigue assessment problem, the strain amplitude spectrum calculated from the rainflow matrix is shown in Fig. 1b. The damage potential of the strain spectrum is very low but the monitored spot was subjected to a great number of load cycles.

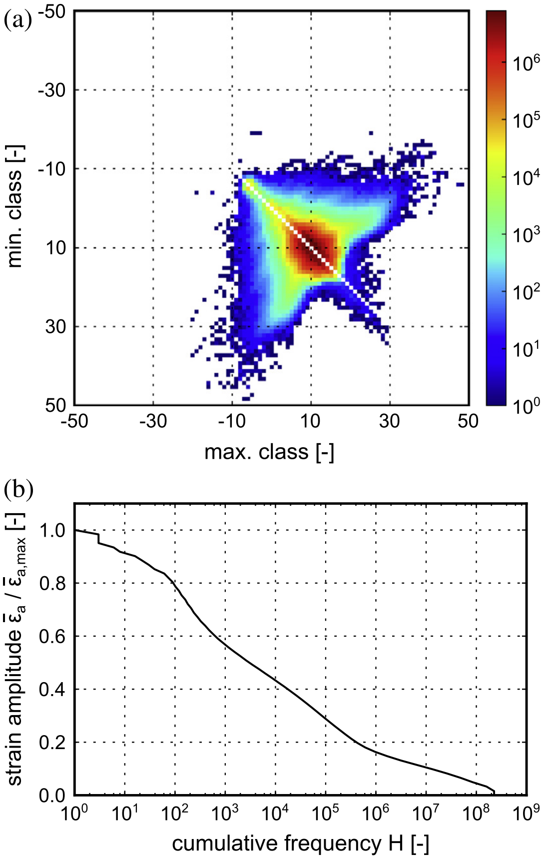

Fig. 1. Rainflow matrix of local strains (a) and specific strain amplitude spectrum corresponding to the rainflow matrix (b). The data were collected on a vertical roller mill over a period of approximately two years and account for 287 days of operational use.

3. Calculation model

With the large amount of strain information, demand is created for a true fatigue assessment of these data. Due to the large sizes and the costs of typical machinery, damage assessment of the data cannot be conducted by fatigue testing complete components. Accordingly a calculation model was developed suitable for the given task, Fig. 2. Bearing in mind the design process using the finite element method and the size of the components, a local approach was chosen. In correspondence with the classical local approach, the material fatigue properties are defined by a damage parameter *S–N* curve, calculated from the cyclic stress–strain curve and strain *S–N* curve:

$$P_{SWT} = \sqrt{(\sigma_f')^2 \cdot (2N_i)^{2b} + \sigma_f' \cdot \epsilon_f' \cdot E \cdot (2N_i)^{b+c}} \tag{1}$$

These material properties are reduced to component fatigue properties using the highly stressed volume approach [3–5] and the surface factor of the FKM-guideline [1]. The highly stressed volume approach is used to include the decrease in fatigue strength $\sigma_{a,V}$ with the increase in size of the loaded specimen or component based on the comparison of the material volumes $V_{90\%}$ in which 90% of the highest local stresses occur:

$$\frac{\sigma_{a,V,2}}{\sigma_{a,V,1}} = \left(\frac{V_{90\%,1}}{V_{90\%,2}}\right)^{v} \tag{2}$$

According to Kaufmann [3] the applicable volume exponent v for the experimentally examined ductile iron EN-GJS-400-15U is defined as follows:

$$v = 0.09 \text{ for } 300\ \mathrm{mm}^3 < V_{90\%} \leqslant 8000\ \mathrm{mm}^3 \text{ and} \tag{3}$$

$$v = 0.01 \text{ for } V_{90\%} > 8000\ \mathrm{mm}^3 \tag{4}$$

These values were determined on the basis of fatigue tests on specimens made from thick walled components. The basic material for these tests was therefore subjected to manufacturing conditions very similar to those of large components made from EN-GJS-400-15U used in heavy plant engineering, making the specified volume exponent v highly suitable for the given task. To include the effects of the surface roughness, the surface factor of the FKM-guideline [1] is utilised:

$$K_{R,\sigma} = 1 - a_{R,\sigma} \cdot \log(R_z/\mu\mathrm{m} \cdot \log(2R_m/R_{m,N,min}) \tag{5}$$

Adequate values for the analysed ductile iron are given with $R_{m,N,min} = 400$ MPa and $a_{R,\sigma} = 0.16$ [1].

The aforementioned effects are used to adjust the damage parameter *S–N* curve, even though this application of a surface factor tends to produce conservative results [6].

With respect to the given task, the description of the service loads is given by a rainflow matrix of local strains. In contrast to the classical local approach, no cycle by cycle analysis is conducted – this information is not available in any case – but, instead, each matrix element is transformed to the damage domain using the damage parameter in the definition of Bergmann [2]:

$$P_B = \sqrt{(\sigma_a + a_{z/d} \cdot \sigma_m) \cdot \varepsilon_{a,t} \cdot E} \tag{6}$$