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Technical note

A novel method for analysis of fatigue life measurements based on modified Shepard method

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ABSTRACT

Fatigue is one of the major reasons of engineering parts failure. Still performing experiments is an effective way for determination of fatigue life. Due to inherent randomness of fatigue data, Bayesian statistics is widely used in the literature. In the present study, modified Shepard method is used to determine the best estimate for fatigue life in replicated tests and results are verified by Bayesian statistical approach. Linear regression method based on ASTM standard is utilized to generate fatigue *S–N* curve, as well as Tikhonov stabilization method is shown to effectively reduce the influences of measurement noise.

1. Introduction

The failures of most engineering parts are generally due to fatigue and to predict the fatigue life of components, empirical correlation and fracture mechanics approach are widely used [1]. The empirical correlation approach uses a damage parameter to correlate with fatigue test results, while the application of fracture mechanics approach is especially used for crack propagation life. In order to predict the fatigue life of specimens, different empirical damage parameters have been proposed to correlate with the fatigue test results [2]. The stress based approach is the most widely used that is applicable to cases of high cycle fatigue. However, the accuracy of life prediction depends greatly on an accurate evaluation of stress concentrations at the fatigue detail [3].

Fatigue is also a complex phenomenon that is affected by various uncontrolled factors that influence fatigue life and cause scattering of measurements. Therefore, a statistical analysis is needed to characterize these variables. Statistical analysis is normally used to analyze fatigue properties and estimate the probability associated with fatigue failure. The analysis is mainly focused on the evaluation of component reliability and prediction of service performance [4]. In general, basic characteristics of data scatter are measured from the simple average of samples and data variation described by a probability distribution functions. Although existence of so-called 'outliers' in the data must be considered in statistical analysis, since utilizing the statistical approach 'blindly' could cause serious errors in computations. The 'outliers' in the data are unexpected glitches in the measurements and may be appeared due to real physical phenomena or an intermittent fault in detectors. The classic way to deal with suspected noise correlations is utilizing Bayesian statistical approach. In this way the 'outliers' would be automatically picked out and be ignored as they can severely skew the results [5]. Most of statistical studies on scattered fatigue life data are focused on the probability analysis aspects by introducing new techniques to improve the accuracy of the reliability prediction model [6–8] or modifying the classic approach for new materials [9,10]. But despite the importance of dealing with outlier fatigue life measurements in replicated experiments, the little attention paid to it and they are commonly ignored [11].

In the present research, two set of St-52 specimens are examined for fatigue life. Both set are manufactured by turning process and tempered to relieve residual stresses due to manufacturing. To investigate effects of surface finishing on fatigue life, one set of specimens undergoes finishing process to achieve polished surface. Fatigue tests are then conducted for both set of specimens under reverse bending. A non-statistic approach based on Modified Shepard is introduced here to determine the best estimate of average of fatigue life measurements and results are then verified by Bayesian

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statistical approach. Finally to achieve the empirical parameters of fatigue *S–N* curve, the maximum value of stresses due to bending is calculated by finite element simulation. Afterward a linear regression technique together with stabilization theory, based on Tikhonov–Morozov approach, is used to reduce the measurement noise and smooth the final solution.

2. Experiments

2.1. Test specimen and fatigue test

Steel specimens are manufactured by turning process from St-52 steel. The chemical composition of the specimen material obtained from EDXRF analysis is C = 0.187 < 0.22, Si = 0.140 < 0.55, Mn = 0.517 < 1.60, S = 0.026 < 0.03 and Cu = 0.031 < 0.55 compared to maximum allowable values according to standard DIN EN 10025. The bulk mechanical properties of the specimen at room temperature are measured from tensile test according to ASTM E8M-04 and Young's modulus of 201GPa, Poisson's ratio of 0.3 and yield and ultimate tensile strengths of 403 MPa and 700 MPa are obtained respectively. Plastic stress–strain properties of steel are given in Table 1.

Dimensions of the test specimen are shown in Fig. 1 where a notch of depth and width of 1 mm is fabricated to ensure that the crack ignition occurs at the vicinity of notch region. To remove surface residual stresses arising from turning process, samples are subjected to stress relief heat treatment of 650 °C for a period of 1 h and then furnace cooled over a period of 24 h [12].

To study effects of surface finishing on fatigue life, half of tempered specimens undergo surface finishing process. The process is carried out by soft material removal from the surface of the specimens to decrease roughness and achieve polished surface. Thus, two set of specimens, called as polished and tempered, are prepared for fatigue test. In order to perform reverse bending fatigue, each specimen is loaded in bending and stresses are cycled by rotating the specimen. Fatigue tests are carried out using a servo-hydraulic universal testing machine, GUNT WP140 [13]. Fatigue tests are then repeated four times for each level of constant amplitude loading to obtain four life measurements. Subsequently bending load is increased in ten steps and fatigue tests are repeated. Finally for each set of polished and tempered specimens, in ten different levels of stress, four values of life measurements are achieved.

2.2. FE simulation

The stress based model for fatigue analysis is used in the present study and the maximum value of 3D stress distributions in specimen is accurately predicted utilizing ABAQUS FE analysis software [14]. Due to the symmetry of the specimen, only a half of specimen is modeled in the simulation and hexagonal shaped meshes with 8-nodded linear brick elements are used. To model a cantilever beam subjected to bending, the displacements of the circumference of the specimen were fixed at the left side and the distributed load was applied on the circumference of the right side of specimen. The stress–strain properties of the model are also assumed to be the same as experimentally measured values of Table 1. The contour plot of the von Mises stress in the vicinity of the notch region is shown in Fig. 2 for load step of 160 N. For all of the load steps, maximum value of stresses occurs at the notch region as it is expected and in complete agreement with the fatigue failure location of specimens. It seems that the notch region, due to the existence of maximum value of the stresses, is the preferential site for fatigue crack nucleation and growth upon the application of cyclic bending loads. The FE simulated maximum value of stresses is also tabulated in Table 2 for each load step.

3. Results and discussions

3.1. Analysis of life measurements based on modified Shepard technique

For each load step, four values of fatigue life, $\{N_k\}$, are measured and presented in Table 3. It is well known that simple average of P measurements, $\bar{N}_{\text{ave}} = \frac{1}{P}\sum_{k=1}^{P} N_k$, does not have enough robustness for being the best estimate because the 'outlier' data are not ignored. To automatically deal with the 'outlier' data and reduce the skewing effect of them, Bayesian statistics with different probability distribution function is usually utilized [5]. Among different probability distribution functions, such as Gaussian, Cauchy and Sivia's distribution, Cauchy distribution is shown to result in the best estimate with the same accuracy as, widely used Sivia's distribution while it involves solving less complicated equations and needs less numerical computations and produces a more realistic overall uncertainty [15]. In the present study, to avoid complicated computations of Bayesian statistical approach, modified Shepard method is introduced to obtain the best estimate of fatigue life. However the results obtained based on modified Shepard method are compared and verified by Bayesian statistical approach with Cauchy probability distribution.

Shepard method is usually used to interpolate the scattered experimental data and produce a continuous surface. The method is based on a distance-weighted, least-squares approximation technique, with the weights varying by the distance of the data points [16]. However to overcome the numerical disadvantages of original Shepard method, different forms of weight function are introduced. The modified Shepard method, without sacrificing the advantages of the original method, has the accuracy comparable to other local methods [17–19].

General form of the interpolant function of modified Shepard method is defined over the continues variable n as below,

$$F(n) = \frac{\sum_{i=1}^{P} w_i(n) f_i(n)}{\sum_{i=1}^{P} w_i(n)} \tag{1}$$

where P is the number of measurements, the shape functions $f_i(n)$ are the local approximations to the best estimate and $w_i(n)$ are the relative weights functions of the inverse distance.

To obtain the final equation governing the best estimate of fatigue life, $\bar{N}$, it is sufficient to change the form of modified Shepard introplant function as below,

$$\bar{N} = \frac{\sum_{k=1}^{P} w_k N_k}{\sum_{k=1}^{P} w_k} \tag{2}$$

Different forms of weight functions are utilized in the literature [15–19], however based on the weight functions introduced originally by McLain [17] and Liszka [18], the following form is proposed by Faghidian [15],

$$w_k = \exp\left[-\alpha d_k^2\right]\left(\frac{1}{d_k^2 + \delta^2}\right)^{\lambda} \tag{3}$$

Table 1
Steel plastic stress–strain properties.

Plastic Strain (%)	0	1	2	4	6	8	9	10	12	15.4
Stress (MPa)	403	463	500	554	600	631	647	658	676	695