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An investigation of the prediction accuracy for volume based HCF models using scaled geometries and scaled loading

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ABSTRACT

The prediction accuracy for the volume based Weibull- and V^* high cycle fatigue models is investigated and compared to the point method. A high number of fatigue tests are performed in rotating bending for single notched cylindrical specimens manufactured in a 12% Cr-steel, a high quality structural steel. The specimens are designed with different highly stressed volume and stress gradient by scaling the geometry, but with the same stresses at the corresponding scaled points. Thus, the maximum stress in the notch is the same. Experiments are performed for three specimen sizes at several stress levels. The volume based Weibull- and V^*-models, as well as the point stress method are fitted to the experimental results. Based on the results, the V^*-model is favored for design purposes.

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1. Introduction

In fatigue design it is desirable to express the severity of the fatigue loading at each material point in a single value. For cyclic stressing it is then necessary to transform the multiaxial stress tensor field, $\boldsymbol{\sigma}(\boldsymbol{x}, t)$, that acts in a component into a fatigue effective stress scalar field, $\sigma_{\text{eff}}(\boldsymbol{x})$. Thus, a local multiaxial HCF criterion must be used. The fatigue effective stress $\sigma_{\text{eff}}(\boldsymbol{x})$ measures the severity of the stress history from a fatigue point of view. There exist mainly three types of local multiaxial HCF criteria. The first type of criteria is based on stress invariants, *e.g.* the criteria suggested by Sines [1] and Crossland [2]. This type of criteria are relatively simple to use and the computational time is short. However, the criteria do not include directional information about the stress state, and should therefore be used with care for stress histories with rotating principal stress directions. The second type of local HCF criteria are criteria based on the critical plane approach. Examples of these criteria are the criteria suggested by Findley [3,4], McDiarmid [5], Papadopoulos [6], or Matake [7]. The critical plane criteria are based on the history of the stress vector that acts on a cutting plane at a material point during a load cycle. Since the critical plane in many cases must be numerically searched for at each material point, the computational time might be high. The third type of local multiaxial fatigue criteria are energy based criteria, see for instance [8].

The effective stress computed by use of a local multiaxial HCF criterion can be used in conjunction with different HCF methods. One widely used method in industry, especially in conjunction with a stress invariant based local HCF criterion, is the point method. When the point method is used to design against HCF, the design is performed without consideration of the stress field's distribution within the component; only the fatigue effective stress that acts in the maximum stressed point is used (where $\sigma_{\text{eff,max}} = \max_{\boldsymbol{x}}[\sigma_{\text{eff}}(\boldsymbol{x})]$ is attained). In deterministic design, $\sigma_{\text{eff,max}}$ is compared to a material specific critical stress value (the fatigue limit) $\sigma_{\text{eff,c}}$, which is determined from fatigue tests. If $\sigma_{\text{eff,max}} \geqslant \sigma_{\text{eff,c}}$, fatigue is predicted. If instead probabilistic design is used, the critical effective stress $\sigma_{\text{eff,c}}$ is assumed to vary from component to component according to a given statistical distribution, and $\sigma_{\text{eff,max}}$ then gives the failure probability, p_f, of the component. The local maxima of σ_{eff} at notches may also be considered. Then a probability of failure at each notch can be estimated. The main advantage of a probabilistic approach is that the inherent scatter in HCF properties is modeled.

It is well-known that not only the stress in the maximum stressed point affects the fatigue risk of a component. The spatial distribution of the stress in the component is important, especially for optimized structures with a smooth distribution of effective fatigue stress and large regions that are stressed to a moderate degree. This is due to the statistical volume effect and the gradient effect. The physical interpretation of the volume effect is that the probability to find a defect somewhere in the component severe enough in order to cause fatigue crack initiation, with subsequent

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Nomenclature

α	weight factor for the hydrostatic stress in Sines HCF criterion
$\boldsymbol{\sigma}$, σ_{ij}	stress tensor and stress component, respectively
$\boldsymbol{\sigma}_{\mathrm{alt}}, \boldsymbol{\sigma}_{\mathrm{mean}}$	stress tensor for the alternating- and the mean part of the stress history, respectively
λ, q	parameters in the V^{*}-model
σ_{eff}, $\sigma_{\mathrm{eff,c}}$	fatigue- and critical fatigue effective stress, respectively
σ_{h}, σ_{vM}	hydrostatic stress and von Mises stress, respectively
σ_{low}, σ_{int}, σ_{high}	low-, intermediate- and high stress level (given in Sines effective stress) used in the tests, respectively
σ_{th}, σ_{ref}	threshold stress and characteristic fatigue strength, respectively
b	Weibull exponent
E	Young's modulus
e	error between experiments and models
F	force applied to the specimen
J	Jacobian determinant
k	number of failed specimens at a certain stress level
m	number of tested specimens at a certain stress level
N	number of load cycles
n	material function
p_f, p_s	failure- and survival probability, respectively
p_f^{exp}	experimental failure probability
R	load ratio
R_{a}	average surface roughness
S	scale factor
R_{m}, $R_{\mathrm{p0.2}}$	ultimate tensile strength and yield strength, respectively
t, $\boldsymbol{x}$	time and position, respectively
V, V^{*}, V_{th}, V_{ref}	material-, highly stressed-, threshold- and reference volume, respectively
w	Gauss weight

failure, increases as the highly stressed volume increases. A physical interpretation of the gradient effect can be that a fatigue crack that initiates in a highly stressed region close to the component surface, may arrest if the stress below the surface decreases rapidly. Since the point method is based only on the stress that acts in the maximum stressed point, the method is insensitive to the volume- and/or the gradient effect. It is established that the use of a point method to design against HCF does not give satisfactory results [9–11].

One class of HCF models are volume- or area based [10–25]. For this type of models it is assumed that defects distributed within the component volume or at the surface area are the cause of fatigue crack initiation. The failure probability of a component is computed from an integration of the effective stress field $\sigma_{\mathrm{eff}}(\boldsymbol{x})$ over the component volume or area, respectively, *i.e.* the fatigue risk is not predicted by use of the fatigue stress in the maximum stressed point only. The most well-known volume model is the weakest-link volume model suggested by Weibull, see Section 3. It was originally developed to predict scatter in static strength for brittle materials [12]. The model was later transferred to fatigue [13,14]. Since the work in [12–14] was performed, the fatigue prediction accuracy of the Weibull volume model has been further investigated [10,15–23]. In [10,21] it is shown that the model can be used to predict fatigue failure with good accuracy for the failure probability $p_f = 0.5$. In [16–18], the Weibull volume model is applied to a specimen with two notches of different size. As long as the model is tuned and applied to one notch at a time, the prediction capability is good. But, when the model is transferred between the two notches, or applied to tests where the notches act as competing crack initiation sites, the predictions for failure probabilities lower and higher than 0.5 lose in accuracy. From the assumption that defects located at the component surface is the cause of fatigue crack initiation, the Weibull model can be modified by changing the volume integration to an integration of the stress field over the component's surface area [16,24]. In [21], a combined area-volume model is suggested in which the mechanisms for volume- and surface area crack initiation are treated as statistically independent. A correlation between size of the crack initiating inclusions, computed according to the proposal of Murakami [26], and the failure probability computed by use of the Weibull model is shown for smooth specimens subjected to tension–compression. Later, in [22], the combined volume-area model was further developed to account for the effects on the fatigue probability from surface condition and residual stresses caused by case hardening.

Another example of volume and area models are the V^{*}- and A^{*}-models [23]. Similar to the volume model presented by Weibull in [12–14], the V^{*}- and the A^{*}-models also are based on weakest-link statistics, but the probability function is formulated in a different way. In [23], for the same double notched specimen geometry as used in [16–18], it is shown that the fatigue predictions made by use of the V^{*}-model is more accurate than the predictions obtained from the A^{*}-model. Both models are shown to improve the fatigue predictions compared to the predictions made by use of the Weibull volume model.

In [10], models in which the effective stress σ_{eff} that acts at each point $\boldsymbol{x}$ on the component surface is adjusted with the absolute or the relative gradient of σ_{eff} at that point are suggested. The overall largest obtained adjusted stress value is then used in the Weibull distribution to compute a failure probability. In [27], Papadopoulos and Panoskaltsis offer a deterministic relative gradient model based on Crossland's local HCF criterion. In [10,18,27], it is shown that there is a considerable improvement of the predictions obtained by using a gradient model instead of by use of only the point stress. Whether the gradient model provides improved fatigue predictions compared to the Weibull volume model seems to be very material dependent; some materials are more sensitive to the gradient effect than to the volume effect, and vice versa.

In models based on critical distance theory, the fatigue risk is evaluated as function of surface depth of the highly stressed volume [23,28]. The critical distance models are basically gradient adjusted point-stress models.

In this work, fatigue tests are performed in rotating bending for single notched cylindrical 12% Cr-steel specimens. The 12% Cr-steel is a high quality steel typically used in gas turbine industry. The specimens are designed with different highly stressed volume and stress gradient by scaling the geometry. The same maximum stress is acting in the notch. In fact, in all corresponding scaled points, the stress is the same. By fitting the volume based Weibull- and V^{*}-models to the experiments, it is investigated how good volume based models, derived from the assumption that interior defects are the cause of crack initiation, describe the failure probability. This gives a measure of the transferability and the prediction accuracy for the different models. The results are then also

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