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Elastic plastic approximation procedure for notched bodies subjected to thermal transient loadings

Alexander Bosch[a]*, Jürgen Rudolph[b], Michael Vormwald[a]

[a]*Technische Universität Darmstadt, Materials Mechanics Group, 64283 Darmstadt, Germany*
[b]*AREVA GmbH, Lifetime Management, 91052 Erlangen, Germany*

Abstract

Components of power plants are often subjected to thermo-mechanical loading conditions. Thermal loadings alone are strain-controlled loadings, inducing locally high mechanical strains and stresses, which may result in low cycle fatigue issues. Furthermore, these cycles are mixed with numerous cycles of lower stress and strain ranges. Regarding applicable design codes such as ASME, French RCC-M or German KTA, fatigue evaluation of such components can be based on the simplified elastic plastic fatigue analysis as the standard option and alternatively on elastic plastic finite element analysis. With regard to processing of long load-time histories (e.g. within an online or offline fatigue monitoring approach), elastic plastic finite element analyses are too time-consuming and not feasible. In contrast, the simplified elastic plastic fatigue analysis is a comparatively fast method, but may yield overly conservative results (and in some rare cases underestimate elastic plastic strain ranges). This may lead to unsatisfactory results by neglecting important influences (cyclic plastic deformation behavior, load sequence and mean stress). In order to consider effects of load sequence and mean stress in fatigue evaluation, it is necessary to calculate the local stress-strain paths over the entire load-time history, using the elastic plastic deformation behavior of the material. The application of commonly used notch approximation procedures (e.g. Neuber's rule, equivalent strain energy density method) fail under thermo-mechanical loading conditions by overestimating the local stresses and strains.
As a general application e.g. for the purpose of long-term fatigue monitoring, measured or calculated temperature-time sequences have to be transferred to fatigue relevant stress and strain time sequences at critical locations. In order to support this task, a fast approximation procedure will be developed in order to overcome the shortcomings of plasticity estimation as an essential part of the fatigue analysis.

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* Corresponding author. Tel.: +49-6151-23089; fax: +49-6151-23083.
E-mail address: bosch@wm.tu-darmstadt.de

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1. Introduction

By monitoring of components in power and other technical plants, the operators should be qualified to ensure a safe long-term operation with the benefit of a more economical usage of their resources. The realistic consideration of loads and plasticity are two major factors influencing the results of the fatigue analysis. The processing of long load-time histories derived from the monitoring for the fatigue evaluation is only possible under the assumption of a linear elastic material behavior. The feasibility is assured by the proportional interdependence between the loading and the local quantities as well as the applicability of the principle of superposition in case of various load cases.

In the context of a power plant typical loading, because of a thermal loading with high temperature ranges, high elastic plastic deformations may result in addition to purely mechanical induced stresses and strains by internal pressure and external piping loads. Under the consideration of plastic deformations, the linear behavior between stress and strain as well as the principle of superposition does not exist anymore. The computing of a component under variable amplitude loading by application of a nonlinear kinematic hardening rule is very time-consuming and with respect to a huge number of load reversal points, not executable.

Under these conditions, it seems to be more efficient to perform an elastic plastic calculation just at a fatigue critical location of the component, better than to perform an elastic plastic calculation for the whole component over the entire lifetime. The simplified elastic plastic fatigue analysis, utilized by the technical codes [1-3], follows these principles by a linear elastic analysis combined with a local plastification factor (K_e-factor), however in relation to many practice-relevant examples the results show a strong tendency to too short lifetimes [4]. In contrast to this fact, the development requirements to improved K_e or direct methods becomes apparent.

The aim of a new or improved procedure must be to combine the benefits of the two possible methods, either 'fast and conservative' (e.g. Fast Fatigue Evaluation) or 'time-consuming and realistic' (cyclic elastic plastic simulation of the component) toward 'fast and realistic'.

The established method of plasticity correction by the K_e-factor is based on fictitiously elastic calculations taking just the strain ranges into account. Load sequence and mean stresses are usually considered in the design fatigue curve or by means of specific correction factors. By the new method, it will be possible to consider load sequence effects and mean stresses individually for each cycle in a subsequent damage calculation. The aspired solution bases on an incremental procedure, which takes force-controlled as well as strain-controlled (thermal) loadings into account.

Commonly used approximation procedures for the determination of local stresses and strains in notched bodies, for example Neuber [5], Seeger-Beste [6] or the 'Equivalent Strain Energy Density' (ESED) method [7] require a spatially limited plastic deformation under structural mechanical loadings. In case of an unlimited spatial plastic deformation, additional terms are needed [8]. The applicability of the approximation procedures (mentioned above) for thermal loadings is not given, even for the case of spatially limited plastic deformations, the component behavior influences the local behavior by its geometry and material behavior.

Nomenclature

Variables

δ	incremental step
Δ	range (of stress or strain)
f	incremental plastification factor
F	force
$K_\mathrm{e}, K_\mathrm{n}, K_\nu$	code based plastification factors
σ, ε	stress and strain
S_n	equivalent linearized stress range
S_m	design stress intensity value
S_a	effective stress amplitude for damage calculation