Fraunhofer Institut
Techno- und
Wirtschaftsmathematik

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An improved multiaxial stress-strain correction model for elastic FE post-processing

Berichte des Fraunhofer ITWM, Nr. 152 (2009)

ISSN 1434-9973

Bericht 152 (2009)

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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

AN IMPROVED MULTIAXIAL STRESS-STRAIN CORRECTION MODEL FOR ELASTIC FE POSTPROCESSING

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ABSTRACT

In this paper, the model of Köttgen, Barkey and Socie, which corrects the elastic stress and strain tensor histories at notches of a metallic specimen under non-proportional loading, is improved. It can be used in connection with any multiaxial σ-ε-law of incremental plasticity. For the correction model, we introduce a constraint for the strain components that goes back to the work of Hoffmann and Seeger. Parameter identification for the improved model is performed by Automatic Differentiation and an established least squares algorithm. The results agree accurately both with transient FE computations and notch strain measurements.

KEYWORDS

Jiang's Model of Elastoplasticity, Stress-strain correction, Parameter Identification, Automatic Differentiation, Least-Squares Optimization, Coleman-Li Algorithm

INTRODUCTION

In order to give a reliable lifetime prediction for an elastoplastic metallic body, which is subjected to exterior loads, good knowledge of the local stresses and strains over time is necessary. Numerical analysis may be applied, cf. Figure 1.

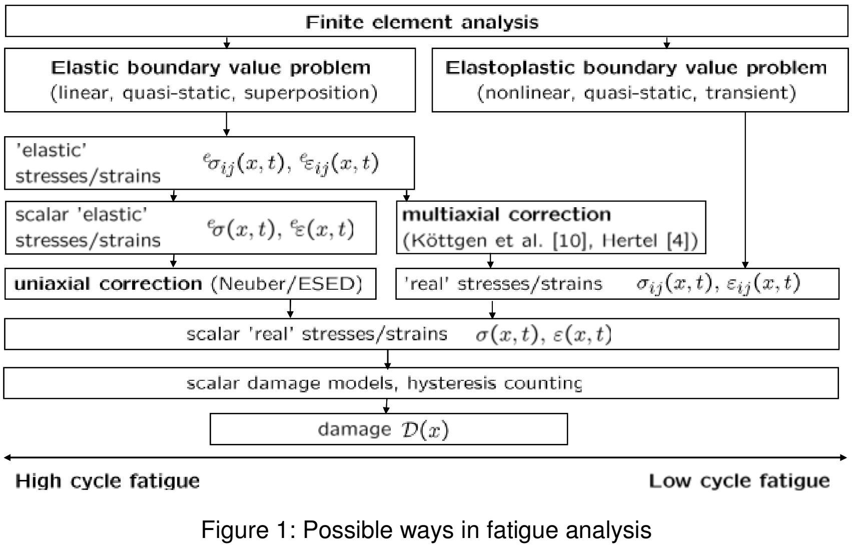

Figure 1: Possible ways in fatigue analysis

In LCF-analysis, the expensive transient elastoplastic boundary value problem with an appropriate elastoplastic constitutive material law $\dot{\sigma}(x,t) = C^{ep}(x,t)\dot{\varepsilon}(x,t)$ is solved in order to receive the ‘real’ elastoplastic stresses σ and strains ε. The following laws are well known and enjoy great popularity: Linear kinematic (plus isotropic) hardening [10, 11], Mroz-Garud [11], Armstrong-Frederick [11], Chaboche [11], Jiang-Sehitoglu [07], and many more …

In HCF-analysis, the much cheaper linear elastic boundary value problem with Hooke’s constitutive law ${}^e\sigma(x,t) = C(x)\,{}^e\varepsilon(x,t)$ is solved to receive the ‘elastic’ stresses and strains ${}^e\varepsilon$. If the locations, where the elastic stress ${}^e\sigma$ crosses the yield stress - and where it thus overestimates the elastoplastic stress σ -, are small and if the response of the body is linearly elastic almost everywhere, local corrections may be applied before projection onto scalar quantities is done. Here *multiaxial Neuber approaches*, cf. Glinka et al. [01, 03, 12], which are based on Neuber’s energy relation

$${}^e\varepsilon_{ij}\,{}^e\sigma_{ij} = \tilde{\varepsilon}_{ij}\tilde{\sigma}_{ij} \quad \text{(for each component),}$$

and *pseudo parameter approaches*, cf. Köttgen et al. and Hertel [05, 08, 09], have been suggested.

But so far, computational results for the cited multiaxial correction approaches differ excessively from transient elastoplastic FE solutions or measurements. In this paper, we propose the following two suggestions for Köttgen’s approach, which turned out to result in significant improvement of existing results: First, we impose *Seeger’s strain ratio relation* on the correction model, second, we perform parameter sensitivity analysis by *Automatic Differentiation (AD)*. Moreover, it is possible to give analytical error estimates (of global nature) for the corrected stresses and strains and a real mathematical justification for Köttgen’s approach in the case of linear kinematic hardening material, cf. [10]. The modified correction model lies somewhere between HCF and LCF in Figure 1: It is fast enough for HCF, the analytical estimates in [10] ensure a small error for the range of LCF.

THE ORIGINAL STRESS-STRAIN CORRECTION MODEL OF KÖTTGEN

The model we consider is the pseudo parameter model of Köttgen et al. [05, 08, 09], which is called the ‘${}^e\sigma$-approach’ therein. We simply name it ‘Köttgen’s model’. The input ${}^e\sigma(t)$ at a fixed point x of the body and a set of (fictive) pseudo or ‘elastic’ parameters govern the movement of a (fictive) ‘elastic’ yield surface in a (fictive) ‘elastic’ stress space with a constitutive elastoplasticity law, which is appropriate for the material.

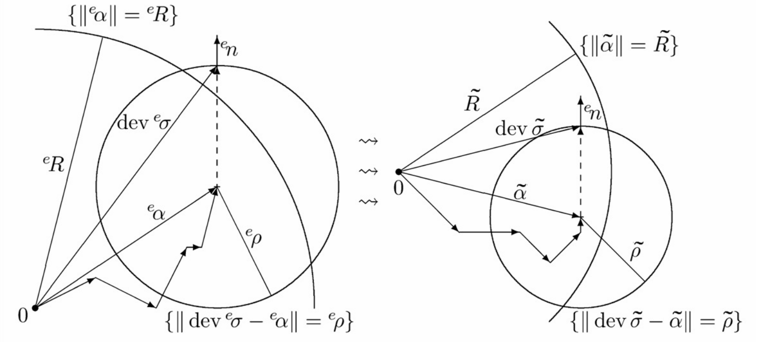

Figure 2: The ‘elastic’ stress space (left-hand) and the ‘correcting’ stress space (right-hand) in connection with Jiang’s constitutive model

The movements in the ‘correcting’ stress space with a ‘correcting’ yield surface are simultaneous to the movements in the elastic stress space with the *same* yield surface normal ${}^en(t)$. Here the real material parameters together with the constitutive material (the same as in the elastic stress space) uniquely determine the evolution. Output of the correcting stress space is the corrected stress $\tilde{\sigma}(t)$ (and the corrected plastic strain $\tilde{\varepsilon}^{pl}(t)$, together with Hooke's law $\tilde{\varepsilon}^{el}(t) = C^{-1}\tilde{\sigma}(t)$ yielding the corrected total strain $\tilde{\varepsilon}(t) = \tilde{\varepsilon}^{el}(t) + \tilde{\varepsilon}^{pl}(t)$). For illustration cf. Figure 2, for details the reader is referred to [10] or the appendix in [08].

For linear kinematic hardening material, it is possible to write down the best choice for the pseudo parameters in an abstract fashion, cf. [10]. For more complex material laws, the best choice of pseudo parameters is still an open question, but for practice it is sufficient to determine them by least-squares-fitting.

THE MODIFIED CORRECTION MODEL

We suggest to modify Köttgen's model [08, 09, 10] by the introduction of Seeger's strain-ratio constraint for sharply notched axles [06]. This results in

$$\frac{{}^{e}\varepsilon_{11}(t)}{{}^{e}\varepsilon_{22}(t)} = \frac{\tilde{\varepsilon}_{11}(t)}{\tilde{\varepsilon}_{22}(t)}, \tag{1.1}$$

where 1 and 2 denote the local coordinate system directions, which are tangential to the notch root: 1 is the longitudinal direction, 2 is the circumferential direction, as it is displayed in Figure 3.

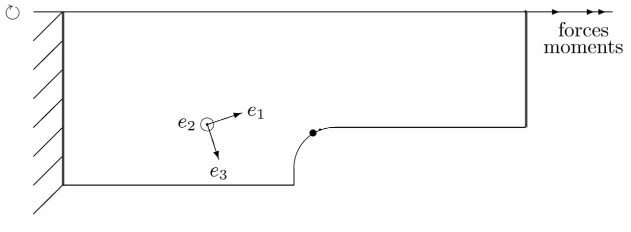

Figure 3: Choice of local coordinate system

Relation (1.1) constitutes a hard algebraic constraint (with given left-hand elastic strain ratio) on the differential equations of the Köttgen model, thus, it becomes differential-algebraic. An appropriate predictor-corrector algorithm for its integration is given in [10]. We give two reasons, why to impose relation (1.1) on the correction model.

First, it is proved in [10], that it is *inherently impossible* for the original correction model to approximate each component of the plane stress tensor for uniaxial and biaxial loading. The reason is one of the main drawbacks of Köttgen's model, namely that the difference of the corrected stress deviator $dev\,\tilde{\sigma}$ and the corrected backstress $\tilde{\alpha}$ is coupled in a simultaneous manner to the difference of the elastic stress deviator $dev\,{}^{e}\sigma$ and the (fictive) 'elastic backstress' ${}^{e}\alpha$. I.e. the tensors $dev\,{}^{e}\sigma - {}^{e}\alpha$ and $dev\,\tilde{\sigma} - \tilde{\alpha}$ are collinear at any time, see the dashed tensors in Figure 2. Equivalently, the yield surface normals in both stress spaces coincide. For biaxial loading, the elastic stress is trapped in a plane, consequently so is the corrected stress. Therefore, it is clear that the existent results for the plane stress tensor [05, 08, 09] cannot be accurate in all components.

Second, the algebraic constraint (1.1) is motivated by Seeger's observation that in sharply notched regions, the relation

$$\frac{{}^{e}\varepsilon_{11}(t)}{{}^{e}\varepsilon_{22}(t)} \approx \frac{\varepsilon_{11}(t)}{\varepsilon_{22}(t)} \tag{1.2}$$

for the elastic FE and the elastoplastic FE strain holds approximately, cf. [06]. So it is very natural that the corrected total strain should satisfy the same relation. Observation (1.2) is purely empirical, a rigorous mathematical justification is still an open question. (For the case of combined axial tension and circumferential torsion, the elastic ratio at the left-hand side in (1.2) is a constant, independent of t.) Rule (1.1) gives additional information into the correction model, and it enforces the corrected stress tensor $\tilde{\sigma}$ to break out of its plane as it is shown in Figure 4.

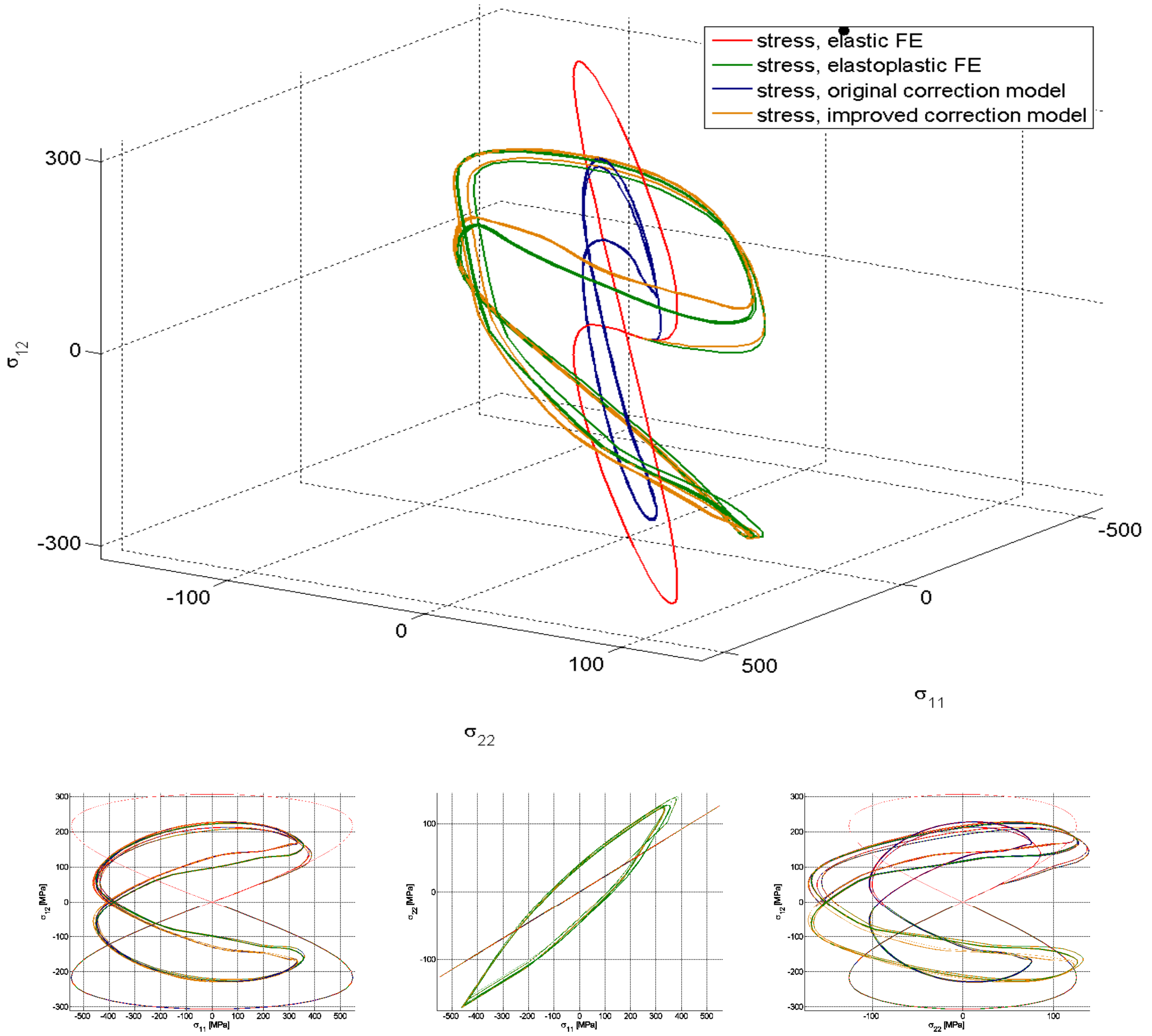

Figure 4: Elastic FE stress, Elastoplastic FE stress, original model and improved model

PARAMETER IDENTIFICATION

The need to determine a huge amount of pseudo parameters is a drawback both of the original and of the improved correction model. This is a big problem especially for constitutive models, where the number of material parameters is already large. For the model of Jiang and Sehitoglu [07] for example, the number of material parameters that have to be identified lies somewhere between 40 and 80. For the correction models considered, there is a need for additional 40 – 80 pseudo parameters. For the nonlinear large-scale parameter identification, we use the well-established trust-region algorithm of Coleman and Li [02]. The latter is implemented e.g. in the Optimization-Toolbox of MATLAB. It can be used for curve fitting in the least-squares sense, i.e.

$$\sum_n \left\|\tilde{\sigma}(t_n)-\sigma(t_n)\right\|^2 \to \min \qquad \text{and} \qquad \sum_n \left\|\tilde{\varepsilon}(t_n)-\varepsilon(t_n)\right\|^2 \to \min .$$

Constraints, as for example the positivity of some parameters, can be taken into account as well. It is a gradient based algorithm, therefore one has to evaluate the partial derivatives of the corrected stresses resp. strains with respect to the parameters, i.e. $\partial\tilde{\sigma}(t_n)/\partial p_i$ and $\partial\tilde{\varepsilon}(t_n)/\partial p_i$. In order to do so, it is very effective and convenient to use the Automatic Differentiation (AD) technique [04], which computes the partial derivatives *analytically exact* in parallel to the integration of the differential-algebraic equations of the correction model.

RESULTS AND CONCLUSION

A first example, which illustrates the improvement of the correction model and where we target at elastoplastic FE computations, has already be given in the foregoing section, cf. Figure 4.

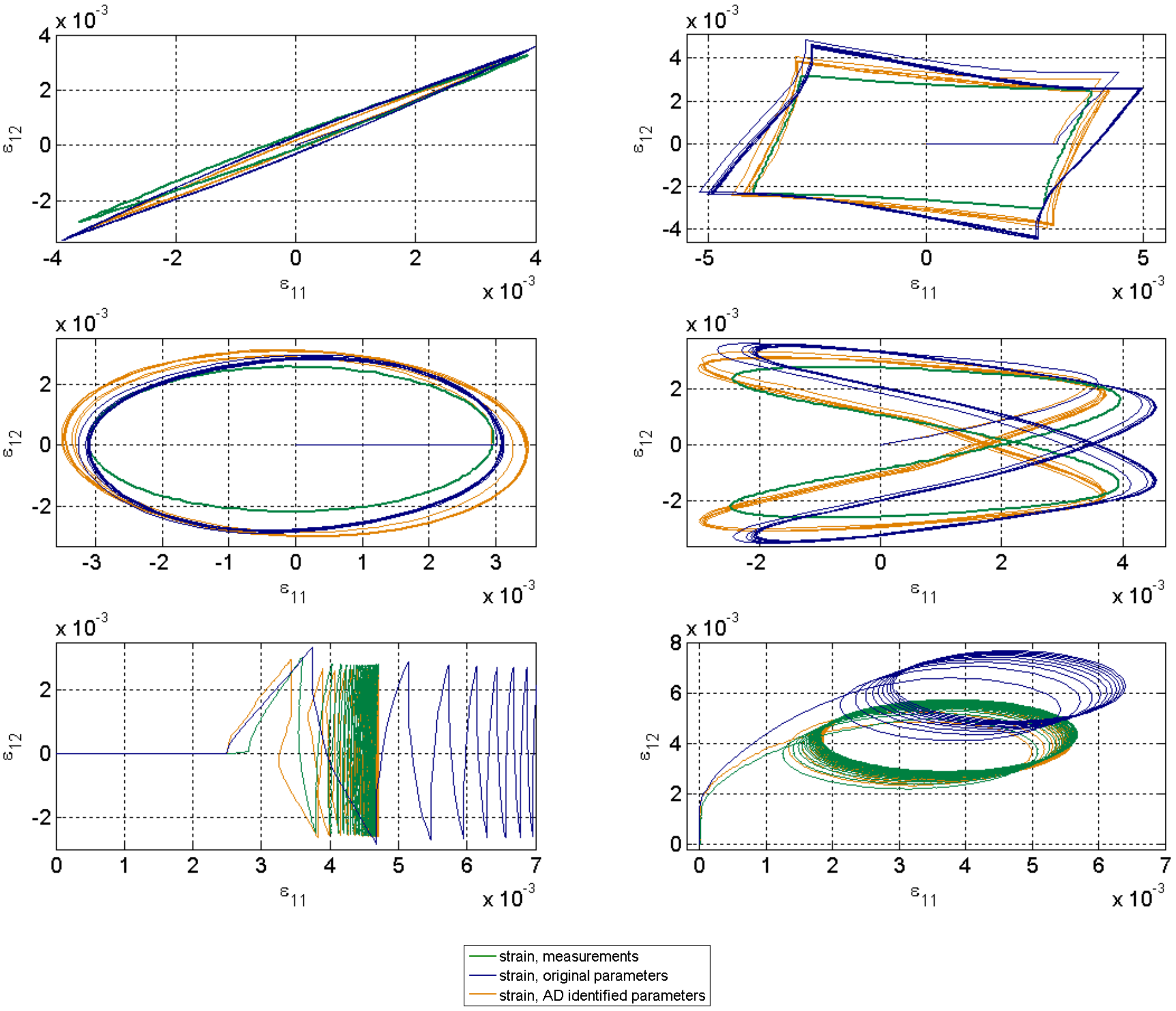

Figure 5: Measurements, original correction model by Köttgen [08, 09] with parameters from Hertel [05], improved model with parameters via AD, cf. [10]. Six different loading paths are displayed.

In a second example, we compare the improved model with strain measurements at the notch root of an axle, made of S460N steel. Here we continue the work of Hertel [05]. As the material exhibits the ratchetting effect, all computations have been performed with Jiang's [07] constitutive model, where 82 parameters have been identified by AD and the Coleman-Li algorithm. The results have been obtained after 20 Coleman-Li iterations. Compared to simple sensitivity computation via Finite Differences ('Exterior Differentiation'), a speed-up of five has been obtained with the tapeless AD-forward mode.

The essential thing from the physical point of view is, that our improved version of Köttgen's model together with Jiang's model and appropriate parameters is in fact able to reproduce the complex transient and highly nonlinear elastoplasticity effects accurately, based on a few linear elastic FE unit load cases, avoiding full transient nonlinear elastoplastic FE computations. (As a pointwise postprocessing it is clearly much faster than elastoplastic FE.)

The results for the circular loading path (left column, middle line in Figure 5) are not completely satisfactory; they could be improved by the use of Döring's constitutive law, which takes out-of-phase phenomena better into account.

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