Phenomenological Modeling of Strain-Range Dependent Cyclic Hardening

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Field of Study: Mechanics of Rigid and Deformable Bodies and Environment

Introduction

Low-cycle fatigue (LCF) is a part of the fatigue phenomenon, where loading implies higher nominal stresses than the yield strength. The maximum number of cycles to failure for common steel-like materials is usually less than thousands of cycles.

The prediction of LCF on real mechanical components consists of two key features - modeling of material response and choosing the appropriate criterion of failure. The appropriate criterion of failure predicts when a failure occurs in a mechanical component depending on loading conditions and its history. Loading conditions are stress and strain tensor fields.

In low-cycle fatigue, the yield strength is exceeded in a large volume of material, the plastic deformations occur and the relationship between stress and strain is no longer linear - on the contrary, it can be very complex.

For example, austenitic stainless steel 08Ch18N10T shows so called strain-range dependent cyclic hardening, as can be seen in Figure 1. For this material it means that it shows almost no cyclic hardening for low-loading conditions, a saturation of material response occurs under constant cyclic loading conditions and material is cyclically stable. But it shows continuous cyclic hardening with no saturation of material response under high-loading conditions. This phenomenon has to be somehow reflected in the material model if the fatigue prediction should give a satisfactory result.

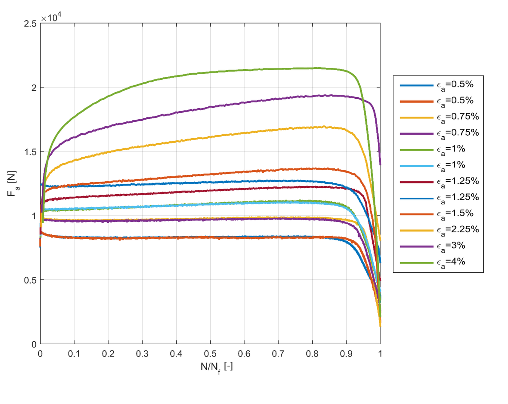


Fig. 1: Illustration of strain-range dependent cyclic hardening of 08Ch18N10T stainless steel

Motivation

In the framework of the grant project of Czech Technological Agency TA04020806, extensive experimental research program of the LCF of austenitic stainless steel 08Ch18N10T has been done. The most advanced suitable model, that can predict strain-range dependent cyclic hardening of this material, while still holding back the number of material parameters, turns out to model of cyclic plasticity developed by R. Halama et al [A1].

This (original) model shows excellent prediction capability for uniaxial loading conditions. It also predicts well the response of notched specimens on three different notched geometries. Under torsional loading conditions, it does predict the material response well only for lower loading levels, see Figure 2a, and over-predicts cyclic hardening of 08Ch18N10T steel for higher loading levels, see Figure 2b.

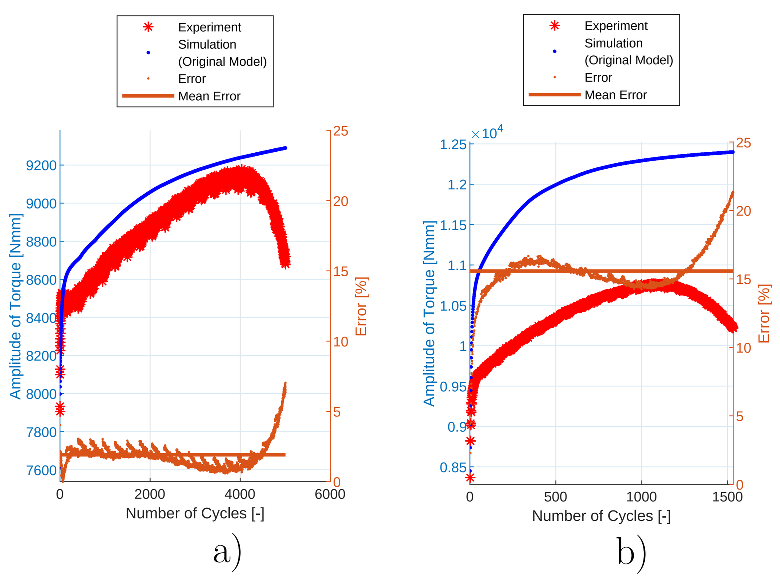


Fig. 2: Experiment vs. simulations, specimen: a) NT-1, b) NT-6

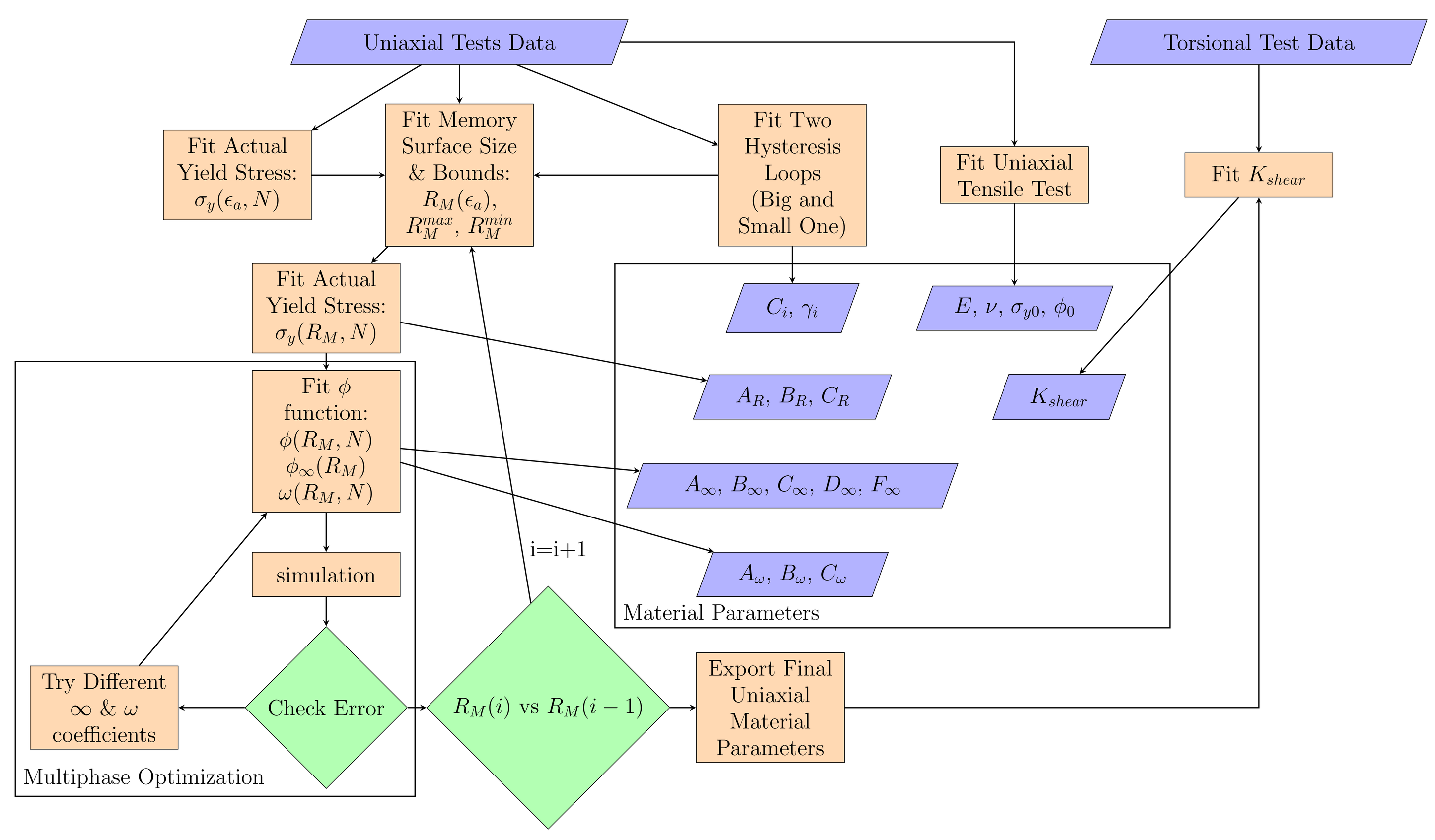
In order to minimize the observed over-prediction under torsional loading conditions, a new formulation of material model is needed.

Objectives of the Doctoral Thesis

The main objective of the thesis is to propose a new formulation of a constitutive model that can predict the response of the material for uniaxial loading conditions as well as for the torsional loading conditions. The key steps to achieve this goal are:

1. **The proposition of modification:**
   Modifications of the original model will be proposed and new constitutive relations will be described.
2. **Calibration of material parameters:**
   The material parameters of the newly proposed model will be identified for 08Ch18N10T austenitic stainless steel. The identification process will be described step by step, the new set of material parameters for 08Ch18N10T steel will be presented.
3. **Implementation into FE:**
   The newly proposed model will be implemented into commercial FE software Abaqus as a user subroutine USDFLD. The algorithm of the subroutine as well as the full Fortran code of the subroutine will be presented.

Material Parameters Identification



Implementation of Proposed Model into Finite Element Analysis

New material model is implemented into commercial FE software Abaqus 6.14 as the user defined field (USDFLD) subroutine. The full Fortran code of the subroutine is published in the thesis and also in [A2].

Results and Outcomes

New material model and new calibration method was proposed. Material parameters was identified for 08Ch18N10T austenitic stainless steel.

Experiments has been simulated using the new material model and compared with simulation results of the original model. For uniaxial loading, both models has similar prediction capability (see Figure 3a and Figure 3b). But the new model predicts better (by 12%) the higher loading levels of torsion (see Figure 3d) with only slight deterioration in prediction (by 3%) for lower levels of loading (see Figure 3d). which can further be balanced by optimizing the new material parameter K_{shear}.

Other noticeable outcome of the thesis is the implementation of new material model into FE software Abaqus as the USDFLD subroutine.

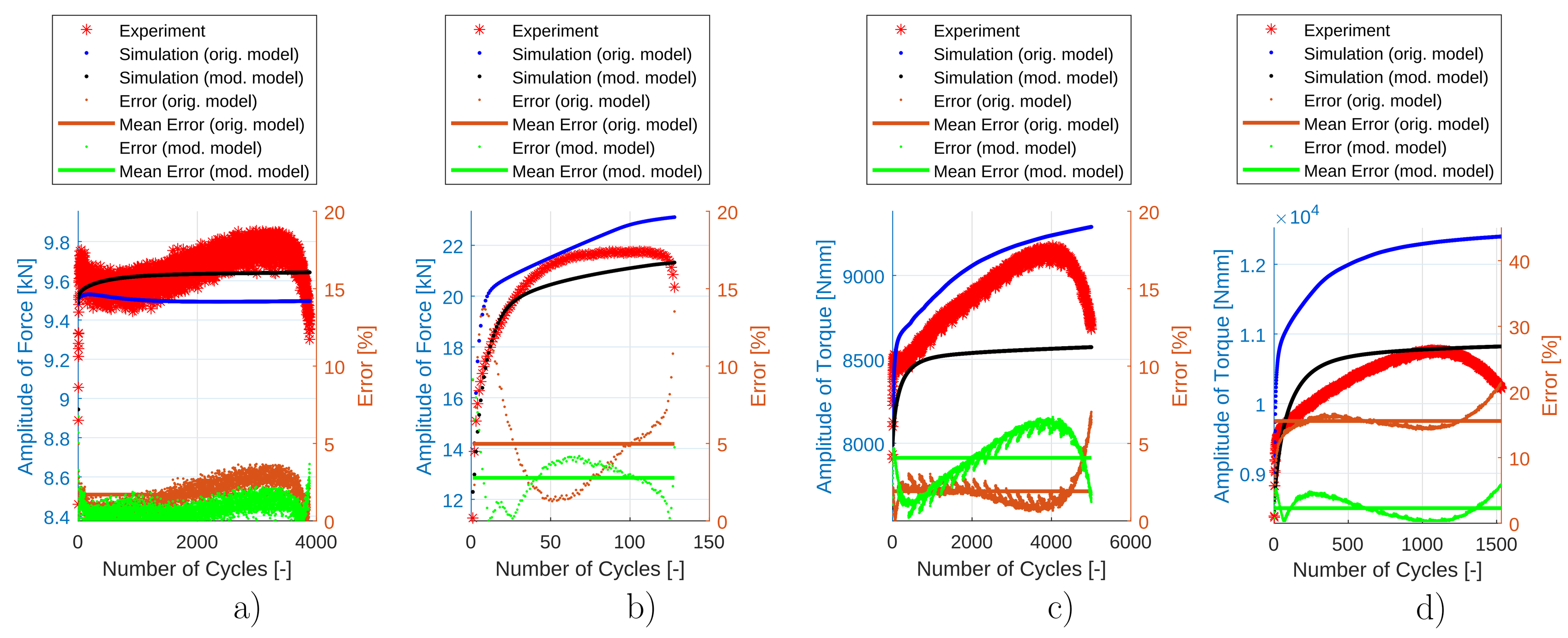


Fig. 3: Experiment vs. simulations, specimen: a) E9-4, b) E9-17, c) NT-1, d) NT-6.

Conclusion and Future Work

Conclusion

The fulfillment of the main objectives:

1. **Proposition of modification:** The new formulation of the material model is proposed and is also published in [A2]. The new formulation of isotropic hardening as a non-linear function of accumulated plastic strain p is proposed. Newly, the memory surface for isotropic hardening and the memory surface for kinematic hardening are defined. The new memory surface limits are defined.
2. **Calibration of material parameters:** The new calibration procedure of material parameters is proposed. It uses the incremental FEA-like simulations of material response for fitting material parameters and multiple optimization procedure to fit the material parameters as precisely as possible. Material parameters are identified for 08Ch18N10T austenitic stainless steel.
3. **Implementation into FE:** Proposed material model is implemented into commercial FE software Abaqus in the form of the user-defined field subroutine (USDFLD) written in Fortran.

The newly proposed model shows practically the same prediction capability as the original model [A1] for uniaxial and notched specimens, but significantly better prediction capability for torsional loading.

Future Work

Proposed model has been developed and tested for the dominant tensile or torsional loading. The next logical step is to verify the proposed model for combined loading conditions, for example, a proportional combination of tension and torsion and possibly propose another modification to include these loading conditions.

Publications and Other Achievements of the Author Related to Topic of the Thesis

[A1] Halama, R., Fumfera, J., Gál, P., Kumar, T., Markopoulos, A. Modeling the Strain-Range Dependent Cyclic Hardening of SS304 and 08Ch18N10T Stainless Steel with a Memory Surface. *Metals*, 9(832):1-26 (2019).

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