Calibrated Modeling and Simulation of Cyclic Thermal Stress Induced Fatigue in AISI 316L Stainless Steel

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ABSTRACT

Thermo-mechanical fatigue has an important influence on the lifetime of components belonging to the primary cooling circuit of a nuclear plant. To reproduce the relevant boundary conditions including variable amplitude low cycle fatigue and ratcheting, an experiment that mimics the cyclic thermal shock loading is performed. To correctly describe the mechanical behavior of stainless steel grade 316L under the prescribed conditions, a Chaboche-type constitutive model with 5 internal variable dependencies is proposed, calibrated and implemented in a commercial finite element code. A finite element thermal stress analysis performed on a case study using this advanced constitutive law is presented. An evaluation of the accuracy loss introduced by reduced material descriptions not accounting for temperature and strain amplitude dependency is discussed.

INTRODUCTION

Thermo-mechanical fatigue is a failure mechanism that is relevant in the context of the structural integrity and safety of nuclear power plants. In the primary cooling circuit, different phenomena, such as thermal striping and turbulent mixing of the coolant, can lead to cyclic thermal stresses, which in turn can induce fatigue damage when the stresses are of sufficient magnitude. Under cyclic loading, stainless steel AISI 316L, which is frequently used in the primary cooling circuit of a nuclear reactor, has a relatively low flow stress, and therefore low cycle fatigue damage can easily occur under cyclic thermal loading. Under various loading conditions, for example when the thermal loading is asymmetric or when the material behavior includes cyclic softening, (local) ratcheting may occur.

When using the local strain approach and a continuum damage accumulation criterion within a finite element framework to estimate the lifetime of the material in a structural component, one needs a constitutive material description that correctly returns the cyclic stress response of the material. In a technological environment, one needs to be able to calibrate such a material description using a limited set of experiments, which limits the complexity one can use for the constitutive material description. In this contribution we report experience with the calibration of a cyclically evolving version of a Chaboche-type, decomposed material model, including its application in combination with a calibrated, multi-axial damage accumulation model for the prediction of short crack propagation in notched specimens under cyclic thermal shock.

MATERIAL CHARACTERIZATION

A set of specimens is sampled from a batch of stainless steel grade 316L from a 20 mm thick hot rolled plate. Blocks with a length of 110 mm along the rolling direction and a 20 mm wide square cross section are extracted from the plate. From these blocks uniaxial fatigue specimens are manufactured according to the standard ASTM E 606-4 [1]. Specimens were extracted at sufficient distance from the edge of the plate to eliminate data scatter caused by microstructural variations typically observed at the edge of rolled sheet metals.

Table 1. Chemical Analysis [wt%] of the 316L Batch

Material	C	Si	Mn	P	S	Cr	Ni	Mo	N
316L	0.024	0.46	1.59	0.039	0.001	17.5	12.5	2.55	0.086

In table 1 the chemical composition is listed for reference. The manufacturing sequence of the material consists of hot working, solution annealing (at 1050−1080˚C), quenching in water and finally pickling and grinding. The plate material in the as received condition shows a microstructure characterized by a precipitate free austenite matrix with some inclusions, annealing twins and an average grain size of about 50µm.

CALIBRATION EXPERIMENTS

Strain controlled low cycle fatigue (LCF) experiments are executed according to the ASTM standard [1] using a 250 kN uniaxial Schenk Hydropuls fatigue bench using an extensometer with an initial gage of 20 mm. The LCF tests are performed with three different strain amplitudes (i.g. 0.40, 0.65 and 1.00%) using an imposed strain path with ramp waveform with a cycling period that is changed in order to obtain a constant strain rate over all experiments (equal to 0.32%/s). The experiments are run at two constant temperature levels, namely room temperature and 200˚C.

In addition to the LCF experiments, ratcheting experiment are performed to calibrate the material response to a drifting mean strain. In these experiments the imposed strain path is a superposition of a constant amplitude ramp waveform and a linearly varying mean strain. The ratcheting rate is defined through the ratcheting step, which is the accumulation of the total shift of the mean strain within a cycle. When the magnitude of the mean strain reaches 5% it is kept constant and the experiment is continued until failure. The ratcheting tests are also performed at two constant temperatures, using three strain amplitudes (as in LCF experiments) and four different ratcheting rates (i.e. +0.10, +0.01, -0.10 and -0.01%/cycle).

CONSTITUTIVE MODELING

The constitutive material description is a temperature dependent, 3-component Chaboche model [2] in which the model parameters are dependent on various internal variables that evolve with cyclic plastic deformation. The equations governing the constitutive model are the following:

$$F = J_2(S - X) - R - Y_0 \tag{1}$$

$$\dot{X}_i = {}^2/_3\, C_i \dot{\varepsilon}_p - \gamma_i X_i \dot{p} \tag{2}$$

with F the yield condition, J_2 the second invariant operator, S the deviatoric stress tensor, X the kinematic back stress tensor, R the isotropic hardening and Y_0 the initial yield stress. The back stress tensor is decomposed into 3 terms i, which evolve as defined in equation (2) with the plastic strain rate $\dot{\varepsilon}_p$ and the accumulated plastic strain rate $\dot{p}$. C_i and γ_i are model parameters that depend on the accumulated plastic strain p, the cyclic plastic strain amplitude ε_a^p, the mean plastic strain ε_m^p, the ratcheting rate $\dot{\varepsilon}_r$ and the temperature T. Using an intricate calibration procedure [3] the parameters of the constitutive material description are fitted to the experimental data and collected in tabular functions from which their values can be interpolated in a finite element environment. An illustration of the quality of the calibrated model is shown in figure 1.

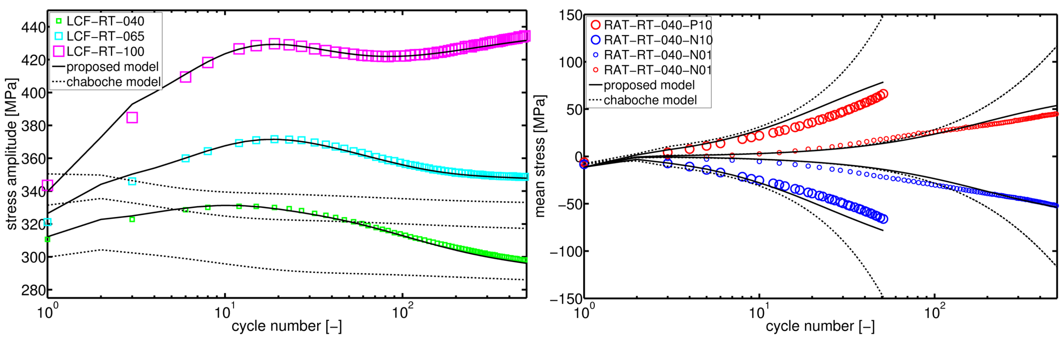

Figure 1. The cyclic stress response of the calibrated material description under LCF and ratcheting conditions compared to the experimental data. In the legend LCF refers to low cycle fatigue with the indicated temperature (RT stands for room temperature) and total strain amplitude (e.g. 065 meaning 0.65%), RAT to ratcheting performed at the indicated ratcheting rates (e.g. P10 meaning a positive-tensile ratcheting rate equal to 0.10% mean strain per cycle). The standard Chaboche model is shown for comparison.

THERMAL STRESS APPLICATION

To evaluate the benefit of calibrating a material description that is dependent on temperature, cyclically accumulated plastic strain, cyclic plastic strain amplitude, cyclic mean strain and the ratcheting rate a computational experiment is performed. In this experiment a notched ring specimen is submitted to cyclic thermal shocks, therewith inducing low cycle fatigue type cyclic plastic deformation in front of the notch.

The geometry of the ring specimens is shown in figure 2. The rings are placed in an ambient air environment at a temperature of 25˚C with a heat transfer coefficient $h = 40\ \mathrm{W/m^2K}$. The inner surface is in convectional contact with oil, the temperature of which increases from 50 to 200˚C in 30 minutes, kept at 200˚C for 15 minutes, followed by a thermal shock back to 50˚C in a transition time equal to 10 s and finally kept at 50˚C until a total of 60 minutes period is reached. The heat transfer coefficients for the contact between the oil and the steel are listed in Ref. [4].

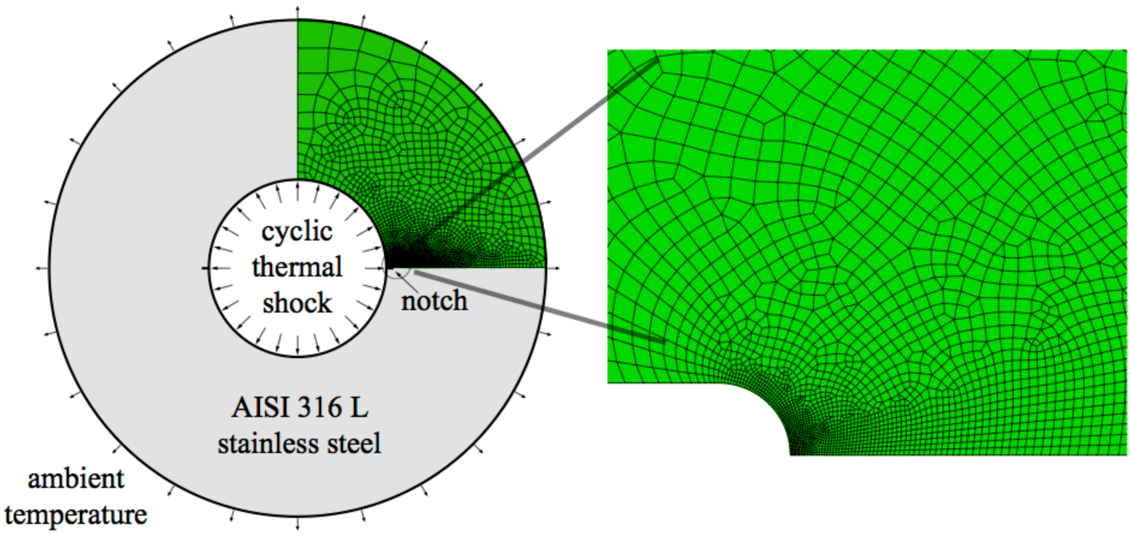

Figure 2. The geometry and the finite element mesh of the notched ring specimen submitted to cyclic thermal shocks.

To evaluate the quantitative influence of the material description on the finite element calculations, simulations using three variations of the material description are used. In the first simulation the complete material description (5 Dep. model) is used, in the second and third a reduced variation is used excluding the temperature dependence in the first variant (4 Dep. Model (T=25˚C)) and the strain amplitude dependence in the third variant (4 Dep. Model (ε ampl=1.00%)). The stress and plastic strain responses, corresponding to the element highlighted in figure 3 at 0.02 mm from the notch tip, are shown in the same figure. The results illustrate that already after very few (e.g. six) cycles, a significant difference is observed between the calculations provided by the complete material description (5 Dep. model) and the two reduced constitutive laws. As expected, those models not accounting for temperature and strain amplitude dependencies, overestimate the magnitude of the stress response of about 10%. This error is reflected by an underestimation of ratcheting of about 10%. It must be remarked that the entity of this difference could significantly increase when a higher number of cycles is considered, considerably affecting the lifetime calculations based on local strain or damage accumulation criteria.

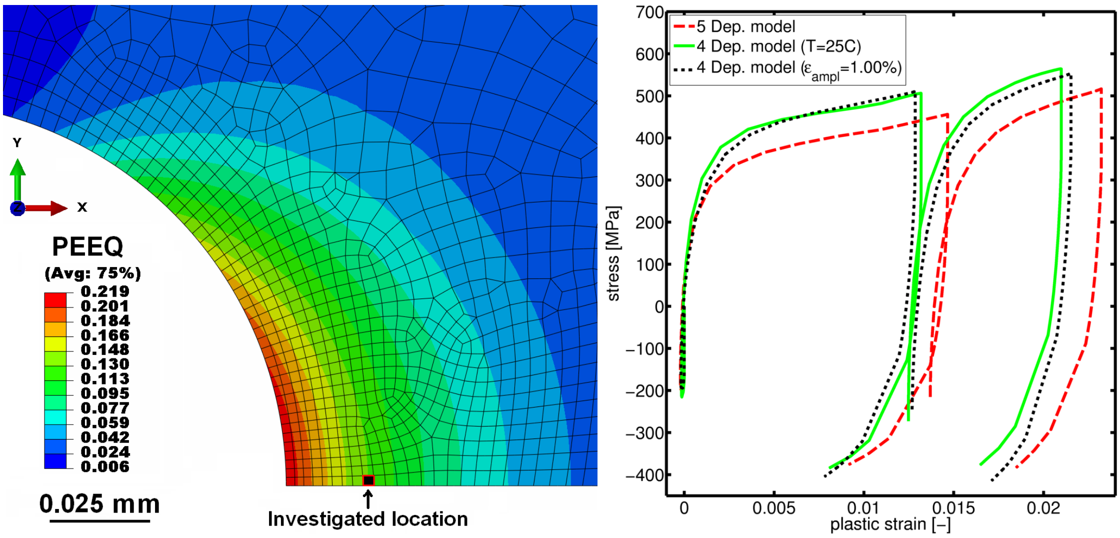

Figure 3. (left) A mesh plot of the accumulated plastic strain distribution near the tip of the notch, indicating the location at which is plotted (right) the y-component of the cyclic stress response versus the plastic strain simulated using: (5 Dep. model) a full dependency material description, (4 Dep. Model (T=25˚C)) a simulation excluding the temperature dependence, and (4 Dep. Model (ε ampl=1.00%)) a simulation excluding the cyclic strain amplitude dependencies. For clarity only the first and 6th cycles are plotted.

CONCLUSIONS

In order to provide an elasto-plastic material description suitable for cyclic loading conditions, including variable amplitude and ratcheting, an evolutionary modification of a 3-component Chaboche model is proposed. In spite of a reduced calibration complexity, the proposed model demonstrates to describe the material behavior with an acceptable accuracy, comparable with the one achieved by more advanced constitutive material descriptions with substantially more (and strongly coupled) parameters.

The material description is calibrated to return the correct material response to cyclic deformation taking into account its variation with temperature, strain amplitude and mean cyclic strain. In an exemplary case study of notched ring specimens submitted to cyclic thermal shocks the significance of the quantitative calibration of the material description for the outcome of a finite element prediction of the transient stress-strain distribution in a component is illustrated.

ACKNOWLEDGEMENT

Swissnuclear is acknowledged for continued funding through the PLiM project (swissnuclear frame contract No 1310).

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