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Implementation of MAKOC cyclic plasticity model with memory

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ABSTRACT

This paper deals with the description of implementation of the advanced cyclic plasticity model called MAKOC, which is based on the AbdelKarim–Ohno kinematic hardening rule, the isotropic hardening rule of Calloch and a memory surface introduced in a stress space in accordance with the Jiang-Sehitoglu concept. The capabilities of the MAKOC model are compared with the Chaboche model included in some FE codes. Cyclic plasticity models commonly included in commercial FE software cannot accurately describe the behavior of the material, especially in the case of additional hardening caused by non-proportional loading of the material. This fact is presented on the experimental data set of aluminum alloy 2124T851. Steady state material behavior is studied with regard to the subsequent application in computational fatigue analysis. The cyclic plasticity model developed was implemented into the FE code ANSYS 15.0 using Fortran subroutines for 1D, 2D as well as 3D elements. The integration scheme is described in detail including the method of implementing the model and determining an error map for the proposed MAKOC and Chaboche models. The numerical tangent modulus is proposed to ensure parabolic convergence of the Newton-Raphson method for the MAKOC model. An axisymmetric analysis of 3D Hertz problem was performed to show convergence in the local as well as global iterations.

1. Introduction

Commercial Finite Element software packages usually provide basic material models, which are not able to accurately model all of cyclic plasticity phenomena like non-Masing behavior, ratcheting, mean stress relaxation, cyclic hardening/softening, additional hardening, etc. Generally, if the material is under the cyclic loading causing cyclic plastic deformation, the cyclic hardening/softening appears during the initial cycles. If the real application is under the loading with constant amplitude, this transient loading can be mostly neglected; only the history of stress and strain tensor for one cycle near half-life is considered [1]. In the case of variable amplitude of stress, it is advisable to include a material model with memory, which allows complex description of transient behavior of the material. One of the most frequently used methods is a model with a memory surface of principal stresses proposed by Jiang-Sehitoglu [2] and the concept of memory surface introduced in principal plastic strain space according to Chaboche [3]. The latter methodology is based on the idea that a region exists without the hardening effect (see Ohno [4]). It should be mentioned that the fatigue curve is in bi-logarithmic scale; therefore, even a small change of the stress/strain amplitude will significantly influence the number of predicted cycles initiating a fatigue crack. Therefore, sufficient description of the stress-strain behavior of material plays a key role in the computational fatigue analysis. Combined with suitable fatigue criteria, this methodology can be used even for general multiaxial loading [5]. The development of cyclic plasticity models has also made considerable progress in the description of the anisotropic hardening which is shown by distortion of a yield surface. From the experimental point of view, this approach requires precise criteria to determine the deviation from elastic behavior [6]. One of the most popular mathematical models of yield surface distortion created by Kurtyka [7] shows the efficiency of the model with the yield surface distortion in prediction of the multiaxial ratcheting, see for instance Vincent et al. [8].

It is well known that the transient behavior of materials may be significantly different for proportional and non-proportional loading, which is defined as a loading causing any change of principal stress directions. A complicated interaction of dislocations of some metallic materials may lead to the additional hardening effect. The hardening is also called non-proportional hardening and represents material hardening as a result of non-proportional

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loading. The non-proportional hardening is tested mostly under tension-compression/torsion loading. Intensity of non-proportional hardening depends on material and shape of loading path. Non-proportional hardening of FCC alloys is related to the stacking fault energy [9]. It was found out under strain controlled 90° out-of-phase loading, that the non-proportional hardening is higher for materials with lower value of the stacking fault energy. In order to identify a degree of non-proportionality Tanaka [10] proposed a tensor of fourth order to calculate a non-proportional parameter. The less complex theory was developed by Benallal and Marquis in [11]. The authors used an angle between plastic strain increment and deviatoric stress increment to define the new non-proportional parameter. Both theories follow with subsequent application of the non-proportional parameter in the isotropic hardening rule.

The application of chosen constitutive model requires an incremental approach. Problems with a material nonlinearity are iteratively solved using numerical methods, mostly using the finite element method (FEM). Solution of global equilibrium equations is usually done by means of implicit Newton–Raphson method [12]. After calculating the unknown nodal deformation parameters in each iteration using Newton-Raphson method it is necessary to determine the stress tensor in the integration points of finite elements. This task will be referred to as a local problem, in contrast to global equilibrium equations solution, which will be called global problem. The most popular implicit numerical method for local problem solution is the radial return method [33]. It can be applied also for very robust models [28], but it should be mentioned, that the implementation is efficient only if the consistent tangent modulus is determined, which was shown in [13].

This paper describes in detail the implementation of a robust cyclic plasticity model MAKOC [14] including a memory surface proposed by Jiang-Sehitoglu. The developed model can also characterize the very complex behavior of metallic materials under cyclic loading which is presented through the data obtained by the tests (combination of uniaxial and torsional loading). The proposed model provides unequivocally more precise prediction than the Chaboche model during the simulation of all solved cases. The MAKOC model was implemented into ANSYS program. Some details about using the user subroutine written in Fortran are discussed.

2. Current state of cyclic plasticity theories available in FE codes

Modeling of cyclic plasticity often requires an individual approach [15]. Based on the knowledge so far, some recommendations and general conclusions in usage of phenomenological hardening models can be established. In commercial applications, hardening models based on a single yield surface concept are used. Calculations for materials with initial isotropy are mostly based on the Von Mises yield condition

$$f(\sigma) = \sqrt{\frac{3}{2}(s-a):(s-a)} - Y = 0, \tag{1}$$

where $\boldsymbol{s}$ is the deviatoric part of stress tensor $\boldsymbol{\sigma}$, $\boldsymbol{a}$ is the deviatoric part of back-stress $\boldsymbol{\alpha}$, which states the position of the center of yield surface and Y is the isotropic variable with the initial value corresponding to yield stress σ_Y. The operator „:“ denotes the inner product between tensors. In this concept, the Bauschinger effect stating the size of elastic region ($2Y$) can be described as shown in Fig. 1.

The total strain tensor ε is composed of elastic strain tensor ε_e and plastic strain tensor ε_p as follows

$$\varepsilon = \varepsilon_e + \varepsilon_p. \tag{2}$$

The stress tensor $\boldsymbol{\sigma}$ is calculated using the Hookeś law from the elastic strain tensor

$$\sigma = \mathrm{D} : \varepsilon_e, \tag{3}$$

where $\boldsymbol{D}$ is the elastic material stiffness matrix. The plastic strain increment is driven through the normality rule, which can be expressed as

$$d\varepsilon_p = d\lambda \frac{\partial f}{\partial \sigma}. \tag{4}$$

The plastic multiplier corresponds to the accumulated plastic strain increment

$$d\lambda = dp = \sqrt{\frac{2}{3} d\varepsilon_p : d\varepsilon_p}. \tag{5}$$

The consistency condition

$$df = \frac{\partial f}{\partial \sigma} : d\sigma + \frac{\partial f}{\partial Y} dY + \frac{\partial f}{\partial \alpha} : d\alpha = 0 \tag{6}$$

has to be satisfied (Fig. 2), when the loading point lies on the yield surface and active loading criteria is true

$$\frac{\partial f}{\partial \sigma} : d\sigma \;>\; 0. \tag{7}$$

As previously explained, the yield surface translates and can expand or contract according to the applied hardening rules. The most important nonlinear hardening rules suitable for cyclic plasticity included in commercial FE codes are described in the next section.

2.1. Kinematic hardening rules

All FE codes provides the Prager's linear kinematic hardening [16]. The ANSYS program, which is considered for implementation of the MAKOC model, offers also the multilinear Besseling kinematic hardening model [17] to describe cyclic plastic properties of a material. Both of them are very limited and are not able to describe the ratcheting and relaxation of the mean stress correctly. In this regard, the Chaboche model [1] is more suitable, which is based on the idea of backstress superposition

$$a = \sum_{i=1}^{M} a^{(i)}. \tag{8}$$

The evolution rule for each backstress part is defined according to the Armstrong-Frederick nonlinear hardening rule [18] with a memory term

$$da^{(i)} = \frac{2}{3} C_i d\varepsilon_p - \gamma_i a^{(i)} dp, \tag{9}$$

where C_{i}, γ_{i} are material parameters. In the literature, the Chaboche model mostly appears with 2 or 3 kinematic parts. Initially, the Prager's rule is considered for the evolution of the last kinematic part ($\gamma_M = 0$). In the case of cyclic plasticity modeling, the Chaboche model may be calibrated from the cyclic stress-strain curve using this formula

$$\sigma_a = \sigma_Y + \sum_{i=1}^{M} \frac{C_i}{\gamma_i} tanh(\gamma_i \varepsilon_{ap}). \tag{10}$$

The number of kinematic parts determines the quality of the approximation of the deformation curve, as shown in Fig. 3 for the ST52 material.

For instance in ANSYS, five kinematic parts ($M = 5$) can be used in total. Due to a low number of material parameters and simple ways to get them, the Chaboche model with 2 kinematic parts is quite popular ($M = 2$). The meaning of individual material parameters can be observed in Fig. 4. Moreover, a model can be adjusted from the uniaxial ratcheting test via suitable selection of the parameter γ_M, as described e.g. in [15].

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