International Journal of Plasticity 63 (2014) 18–48

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Numerical comparison of isotropic hypo- and hyperelastic-based plasticity models with application to industrial forming processes

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ARTICLE INFO

Article history:
Received 4 September 2013
Received in final revised form 11 June 2014
Available online 25 June 2014

Dedicated to Prof. Dr.-Ing. Otto Timme Bruhns on the occasion of his 70th birthday

Keywords:
B. Cyclic loading
B. Elastic–plastic material
B. Finite strain
C. Finite elements
Metal forming

ABSTRACT

Industrial forming processes are usually characterized by large plastic strains and rotations of material elements. This emphasizes the importance of reliable finite strain elastoplasticity models in corresponding finite element simulations. The aim of this work is to review and numerically compare two inherently different types of formulations of finite strain elastoplasticity, namely hypoelastic- and hyperelastic-based plasticity models, with special reference to their applicability in forming processes. Both models allow for nonlinear isotropic and kinematic hardening of Voce and Armstrong–Frederick type and were implemented as user material subroutines (UMAT) into ABAQUS/Standard. Several numerical tests were conducted to assess their respective capabilities. Interestingly enough, although both models led to remarkably different results in shear-dominated single element deformation tests, the structural simulations of a deep drawing, draw bending and thermoforming process delivered nearly congruent results. This suggests that both models are well-suited for modeling elastoplastic materials in common industrial forming processes.

1. Introduction

The theoretical development of material models as well as their implementation into numerical methods, e.g. the finite element method, is a time-consuming and challenging task, especially in the context of a large deformation theory. Concerning elastoplastic material models, different strategies exist to extend the infinitesimal theory to the finite deformation range. Consequently, quite a high number of alternative formulations were proposed and discussed in the past (for an intensive yet interesting debate on that topic, see e.g. Casey and Naghdi, 1981). All these formulations, though based on a completely different description of plastic flow, elastic properties as well as stress and strain measures, are identical in the ‘small strain limit’.

In the beginnings of the theory and application of large deformation elastoplasticity, models implemented into finite element codes relied exclusively on hypoelastic-based approaches which make use of an additive split of the rate of deformation tensor into elastic and plastic parts and a constitutive equation for objective stress rates. Pioneering papers in this field were published e.g. by Argyris and Kleiber (1977), Argyris et al. (1978), Hibbitt et al. (1970), McMeeking and Rice (1975) and Nagtegaal and de Jong (1981), to name only a few. However, shortly afterwards several controversial issues appeared in this context, e.g. the non-uniqueness regarding the respective objective rate used in the formulation (Atluri, 1984; Nemat-Nasser, 1982; Perić, 1992), the lack of objectivity of corresponding numerical integration schemes which led to

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http://dx.doi.org/10.1016/j.ijplas.2014.06.003
0749-6419/

the development of incrementally objective algorithms (Hughes, 1984; Hughes and Winget, 1980; Rubinstein and Atluri, 1983) and several artifacts such as e.g. the oscillatory shear stress response under monotonic shear loading (Dienes, 1979; Lehmann, 1972; Nagtegaal and de Jong, 1982) or artificial elastic dissipation (Kojić and Bathe, 1987; Simo and Pister, 1984). The development of the so-called self-consistent Eulerian model (see e.g. Bruhns et al., 1999; Xiao et al., 1997a, 2000) based on the logarithmic stress rate shed new light on the topic since it does not suffer from the above mentioned problems. There is still active research in this area, see e.g. Zhu et al. (2014) for the development of a logarithmic stress-based hypoelastic–plastic model relying upon a finite strain extension of the kinematic hardening rule by Abdel-Karim and Ohno (2000) for infinitesimal plasticity. Recently, the self-consistent Eulerian model has been used to describe the elastoviscoplastic damage behavior of mineral filled semi-crystalline polymers (Balieu et al., 2013) or for modeling shape-memory alloys (see e.g. Müller and Bruhns, 2006; Teeriaho, 2013; Xiao, 2013). Hypoelastic-based plasticity models taking into account elastic and/or plastic anisotropy in combination with nonlinear isotropic and kinematic hardening are also successfully employed in the metal forming community to simulate various industrial processes and predict phenomena such as springback (see e.g. Firat et al., 2008; Haddag et al., 2007; Hama et al., 2008; Oliveira et al., 2007 and Yoshida and Uemori, 2003, to name only a few). Even nowadays many in-built material models in commercial finite element codes exploit classical hypoelastic-based approaches to model finite strain elastoplasticity, especially if small elastic strains are assumed.

Owing to the problems described above, hyperelastic-based plasticity models emerged. They rely upon a multiplicative decomposition of the deformation gradient into elastic and plastic parts and a hyperelastic constitutive equation for the stress. Initial developments in this field were given by Simo (1985) and Simo and Ortiz (1985). This type of models bypasses the aforementioned drawbacks observed in hypoelastic-based plasticity as e.g. elastic dissipation and incremental objectivity, since an underlying free energy potential is utilized and the principle of frame-indifference is satisfied in a trivial manner. Several models based on principal logarithmic strains were established which incorporate either isotropic or combined isotropic–kinematic hardening (see e.g. Eterovic and Bathe, 1990; Cuitiño and Ortiz, 1992; Simo, 1992; Weber and Anand, 1990). Due to an exponential map algorithm utilized to integrate the plastic flow rule, these models retain the simple small strain format return mapping of the infinitesimal theory. However, the mentioned concepts are mainly limited to isotropic elastoplasticity. Thermodynamically consistent formulations were presented which are also amenable to elastic and/or plastic anisotropy of the material (among others, Chatti et al., 2001; Han et al., 2002, 2003; Sansour et al., 2006, 2008) and/or kinematic hardening for arbitrary large deformations, see e.g. Dogui and Sidoroff (1985), Haupt (1996), Lion (2000), Svendsen et al. (1998), and Tsakmakis (1996). In this context, Arghavani et al. (2010, 2011), Dettmer and Reese (2004), Reese and Christ (2008) and Vladimirov et al. (2008, 2009) considered and discussed also several numerical examples on the structural level in detail. The hyperelastic-based approach to model finite elastoplasticity gained widespread acceptance over the last two decades and can nowadays be considered as 'state-of-the-art'. As such, it is a matter of ongoing research in a variety of scientific areas, as e.g. soil plasticity (see e.g. Coombs et al., 2013), damage mechanics (see e.g. Ayoub et al., 2014, Badreddine et al., 2010, Vladimirov et al., 2014) or crystal plasticity (see e.g. Bargmann et al., 2011). The application of anisotropic hyperelastic-based plasticity models in the simulation of structural metal forming processes which involve springback behavior of the material is nowadays likewise well-established (among others, see e.g. Sansour et al., 2007; Vladimirov et al., 2010, 2011).

The available literature is mainly concerned with theoretical aspects of and differences between hypoelastic- and hyperelastic-based formulations (see e.g. Xiao et al., 2006). To the authors' knowledge, the respective practical capabilities of both approaches have rarely been directly compared with each other in more application-oriented examples which seems however worthwhile and interesting (for one among the few counterexamples, see e.g. Chatti, 2010). In this respect, the present work makes a contribution by discussing and comparing two specific hyper- and hypoelastic-based plasticity models with isotropic and kinematic hardening applied in the simulation of forming processes. The presented models are implemented as user material subroutines (UMAT) into the commercial finite element code ABAQUS/Standard. Various sample calculations, as e.g. the simulation of a deep drawing, draw bending and thermoforming process, are performed to assess their respective capabilities.

The paper is structured as follows. Section 2 is concerned with the theory and algorithmic implementation of a general hypoelastic-based plasticity model with combined nonlinear isotropic and kinematic hardening. The main ingredients of the model are presented as the chosen objective stress rate, the split of the rate of deformation tensor into elastic and plastic parts, the yield function and further constitutive equations to close the model. Section 3 addresses a specific hyperelastic-based plasticity model with combined hardening. In addition to the multiplicative decomposition of the deformation gradient into elastic and plastic parts, this model is based on a further split of the plastic part in order to model nonlinear kinematic hardening. The main issues such as kinematic assumptions, formulation of the Helmholtz free energy, thermodynamically-consistent derivation of the constitutive equations and the yield function are regarded. A numerical algorithm is discussed which preserves the plastic volume and the symmetry of the internal variables. Finally, numerical comparisons between the two models both on the Gauss point level and in various forming simulations are presented in Section 4.

2. Hypoelastic-based plasticity model

2.1. Objective corotational rates

In continuum mechanics, the constitutive equations are required to satisfy the principle of material frame-indifference (also called principle of material objectivity). According to this fundamental physical principle, material properties must