International Journal of Plasticity 70 (2015) 126–150

Contents lists available at ScienceDirect

International Journal of Plasticity

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

A new thermodynamical framework for finite strain multiplicative elastoplasticity coupled to anisotropic damage

R. Balieu*, N. Kringos

Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 21 November 2014
Received in revised form 24 February 2015
Available online 25 March 2015

Keywords:
B. Finite strain
B. Elastic-plastic material
B. Anisotropic material
Thermodynamics

ABSTRACT

The thermodynamical framework of an elastoplastic model coupled to anisotropic damage is presented in this paper. In the finite strain context, the proposed model is based on the multiplicative decomposition of the strain gradient into elastic and plastic parts. The anisotropic degradation is introduced by means of a second order tensor and another intermediate configuration is introduced by fictitiously removing this degradation from the plastic intermediate configuration. To enhance the physical meaning of the Mandel-like stress measure work conjugated to the inelastic flow stated in this fictitious configuration, i.e. the "effective stress", a new damage rate tensor is defined with its associated push-forward and pull-back operations. The emphasis in this paper is placed on the description of the interesting properties of the novel definitions of the push-forward and pull-back operations which are discussed through a thermodynamical framework. Furthermore, a specific constitutive model with the plastic and damage flow rules deduced from the restrictions imposed by the second law of thermodynamics is discussed with an application on an asphalt concrete material where the anisotropic evolution of the damage is highlighted.

1. Introduction

The incorporation of degradation of material properties in the context of computational modeling is still a challenge particularly when the material is submitted to large deformations/rotations. Finite strain elastoplasticity or elastoviscoplasticity has been a very active research domain during the past decades and the resulting multiplicative decomposition of the deformation gradient tensor into elastic and plastic parts, originally proposed by Kröner (1959) and Lee (1969), with its associated stress free intermediate configuration is nowadays mainly used in computational mechanics (e.g. Lubliner, 1990; Khan and Huang, 1995; Haupt, 2000). Furthermore, in the aim of coupling elastoplasticity with Continuum Damage Mechanics (CDM), the concept of effective stress (Kachanov, 1958; Rabotnov, 1969) where a fictitious undamaged configuration (effective) is introduced by fictitiously removing all kinds of degradations (e.g. micro-voids, micro-cracks …) has been widely used as it can be found in several famous monographs such as, Lemaitre and Chaboche (1990); Lemaitre (1992); Voyiadjis and Kattan (2005). In the CDM approach, based on the thermodynamics of irreversible processes, a damage variable represents the effects of the microscopical defects on the macroscopic behavior (e.g. Cordebois and Sidoroff, 1979; Chaboche, 1981; Krajcinovic, 1983; Lemaitre, 1985b; Chaboche, 1988; Lubarda and Krajcinovic, 1993; Carol et al., 2001a; Besson, 2009;

* Corresponding author. Tel.: +46 8 790 8710.
E-mail address: balieu@kth.se (R. Balieu).

http://dx.doi.org/10.1016/j.ijplas.2015.03.006
0749-6419/

Celentano and Chaboche, 2007; Voyiadjis and Dorgan, 2007; Voyiadjis et al., 2012; Balieu et al., 2013; Krairi and Doghri, 2014; Brünig et al., 2014, and more). This damage variable is a scalar in the case of isotropic damage evolution (e.g. Krajcinovic, 1983; Lemaitre, 1985a, b; Bonora, 1997; Bonora et al., 2005; Pirondi et al., 2006; Zaïri et al., 2008; Haddag et al., 2009; Ayoub et al., 2011; Balieu et al., 2013, 2014; Krairi and Doghri, 2014, and more) or a tensor (second or fourth order) for anisotropic damage (e.g. Murakami and Ohno, 1981; Chaboche, 1981; Chow and Wang, 1987; Steinmann and Carol, 1998; Menzel and Steinmann, 2001; Brünig, 2003; Doghri and Tinel, 2005; Voyiadjis et al., 2008; Desmorat and Otin, 2008; Notta-Cuvier et al., 2013, 2014; Mengoni and Ponthot, 2015, and more).

In this work, using the standard framework of multiplicative elastoplasticity, the fictitious effective configuration is introduced by removing the degradation from the intermediate plastic configuration (stress-free intermediate configuration) as in the previous work done by Menzel and Steinmann (2003); Ekh et al. (2004); Menzel et al. (2005). This fictitious effective configuration and the standard intermediate configuration of multiplicative elastoplasticity are related via a damage deformation gradient (second order tensor). In this approach, the application of the covariance principle, i.e. material frame indifference, on the free energy with respect to superimposed isomorphism leads to energy equivalence between the plastic intermediate and the fictitious effective configurations. The energy equivalence principle has been widely used in the context of CDM (e.g. Cordebois and Sidoroff, 1979; Chow and Wang, 1987; Hansen and Schreyer, 1994; Steinmann and Carol, 1998; Voyiadjis and Kattan, 2005, 2006; Hammi and Horstemeyer, 2007; Voyiadjis et al., 2008, and more).

Based on the framework developed by Menzel and Steinmann (2003); Ekh et al. (2004); Menzel et al. (2005), a hyperelastic-based constitutive model using the multiplicative decomposition of the deformation gradient into elastic and plastic parts is developed in this work to model anisotropic damage coupled to plasticity. Since no kinematic hardening is introduced in this contribution, only damage and plastic (with proportional hardening) dissipative processes are considered. For the sake of clarity and since it is not the aim of this contribution, several aspects of plasticity such as pressure sensitivity or non-associated plastic flow rule are not investigated and the more straightforward choice of plastic dissipation potential will be used. Moreover, since the degradation of the material is represented by a second order tensor, the proposed model deals obviously with an anisotropic damage evolution (Steinmann and Carol, 1998; Menzel and Steinmann, 2001; Brünig, 2003; Brünig and Ricci, 2005; Brünig, 2001; Brünig and Gerke, 2011). The isotropic and anisotropic evolutions of the damage velocity gradient tensor is defined by introducing a damage potential initially used by Brünig (2003).

Furthermore, in this contribution the internal power of dissipation equivalency is used in order to derive the work-conjugacy between stress and velocity gradient tensors in the plastic intermediate and fictitious effective configurations. The power equivalence hypothesis, initially proposed by Hao et al. (1985), has been used by several researchers to derive constitutive models associated with dissipative processes (e.g. Voyiadjis and Thiagarajan, 1997; Voyiadjis et al., 2004; Al-Rub and Darabi, 2012; Darabi et al., 2012a, b). The well-known elastic Mandel stress tensor (Mandel, 1971), which is work-conjugated to the plastic velocity gradient tensor is therefore used in this contribution and its contravariant–covariant pull-back operation in the effective configuration leads to a nominal (damaged) and an effective (undamaged) stress measures which are very close to each other. In order to overcome this deficiency, the velocity gradient tensor in the fictitious effective configuration is defined by a covariant pull-back operation of the velocity gradient in the plastic intermediate configuration by the damage gradient tensor. The advantages of this definition of the effective velocity gradient tensor as well as its consequence in a thermodynamical point of view are discussed in this contribution. The proposed approach adopts therefore a consistent thermodynamic formulation in the sense of Coleman and Gurtin (1967), i.e. the internal state variable procedure is applied to describe the irreversible thermodynamic processes and, as standard, the Clausius–Duhem inequality and the maximum dissipation principle are used to derive the constitutive equations.

Motivated by the previous work done by Menzel and Steinmann (2003); Ekh et al. (2004); Menzel et al. (2005) and by the lack of a real “effective meaning” of the Mandel stress tensor pull-backed in a classical way in the fictitious effective configuration, the main objectives of this contribution are:

1. To develop a thermodynamical consistent finite strain framework where anisotropic damage is coupled to elastoplasticity by means of an effective configuration where the stress measure work conjugated to the velocity gradient is a real effective measure, i.e. a measure where the damage is fictitiously removed.
2. To propose a constitutive model through this framework which can be easily implemented in a finite element code.

This paper is structured as follows. In Section 2, the basic kinematics used in the proposed framework are introduced briefly. The thermodynamical framework of the proposed approach which includes the definition of the stress measures work-conjugated with the velocity gradient tensors in the different configurations, the thermodynamic restrictions and the derivation of the constitutive equations associated to the dissipative processes are presented in Section. 3. In Section 4, a hyperelastic model as well as the plastic and damage dissipation potentials through the proposed framework are discussed with a brief presentation of their implementation in a finite element context. Finally, before the conclusions of this contribution, the accuracy of the proposed formulation is demonstrated in Section 5 by comparing numerical simulations and experiments carried out on an asphalt concrete material.