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Comput. Methods Appl. Mech. Engrg. 298 (2016) 428–452

Computer methods in applied mechanics and engineering

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Bifurcation investigations of coupled damage-plasticity models for concrete materials

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Received 30 March 2015; received in revised form 8 August 2015; accepted 11 October 2015
Available online 19 October 2015

Abstract

This communication addresses the localization properties of a coupled damage-plasticity formulation for concrete materials to provide information on the onset of material bifurcation and the critical failure modes.

Two separate loading functions are considered, one for damage and one for plasticity. A three-invariant yield surface is used to model plasticity and to consider the significant role of the intermediate principal stress and the Lode parameter on the failure of concrete materials. A non-associated flow rule is employed to control inelastic dilatancy. To model degradation of the elastic stiffness a scalar-valued isotropic damage formulation is introduced based on the total strain energy formulation that is used.

Monotonic and cyclic uniaxial compression experiments are performed on concrete cylinders under displacement control and photogrammetric images are collected for Digital Image Correlation Analysis. The triaxial based damage-plasticity model is calibrated based on these experimental observations and is implemented in Matlab.

Extensive localization analysis studies are performed at the constitutive level for representative load scenarios in the form of non-positive properties of the elastoplastic-damage localization tensor. The contributions of damage, plasticity and coupled damage-plasticity are explored and compared for classical Boltzmann and Micropolar Cosserat continuum formulations.
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Keywords: Concrete materials; Localization; Coupling of three-invariant plasticity and damage

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1. Introduction

A survey of recent concrete literature indicates a rapidly increasing number of proposals to combine plasticity and continuum damage mechanics for the characterization of concrete materials (Lee and Fenves [1], Carol et al. [2], Salari et al. [3], Tao and Phillips [4], Grassl and Jirásek, [5,6]; Cérvenka and Papanikolaou [7], Voyiadjis et al. [8], Grassl et al. [9]). Thereby, it is understood that both damage and plasticity formulations are dissipative in nature, even though they start from very different constitutive concepts. Irrespective of the thermodynamic setting, continuum damage

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http://dx.doi.org/10.1016/j.cma.2015.10.010
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mechanics resorts to the reduction of the initial elastic stiffness properties in form of a Cauchy type elastic secant relationship. In contrast plasticity resorts to the notion of strength and its description of an evolving yield surface.

In the case of scalar damage the entire stiffness tensor is reduced by the scalar valued (1-D) factor, which retains the fundamental construct of linear elasticity (isotropic or anisotropic). Consequently, the main deficiency of continuum damage mechanics is the initial reference stiffness, which does not change when the concrete exhibits strongly dilatant behaviour e.g. in compression when the stress reaches the maximum material resistance. The so-called Reynolds effect of coupling shear and volume change is a classical attribute of granular materials. Therefore, traditional concrete exhibits a transition from compaction to dilatation under increasing axial compression. This transition of volume change is missing in scalar-valued damage models when Poisson's ratio remains fixed (this deficiency cannot be remedied by an isotropic damage formulation based on one or two separate damage variables characterizing volumetric and deviatoric damage processes with no coupling). The other deficiency of continuum damage models is the reversibility of deformations under load–unload cycles, which does not account for permanent deformations.

In the case of elasto-plasticity, it is the question of the flow rule and hence the plastic potential whether the elastic reference stiffness is sufficiently modified by plastic dilatancy controlled by the volumetric portion of the plastic strain rate of the flow rule. In fact, most pressure-sensitive plasticity formulations adopt a non-associated flow rule to reduce the plastic dilatation in granular media and concrete. Clearly, the main attribute of plasticity is the irreversible nature of the plastic deformations under load cycles. Therefore, the main deficiencies of continuum damage models may be corrected by the combination of the two dissipative mechanisms of elastic damage and plasticity.

In this paper a damage-plasticity formulation is adopted to characterize concrete's behaviour, where damage and plasticity functions are two separate functions, as discussed by Grassl and Jirásek [5], [6]. In specific, for plasticity, the three-invariant yield surface of Willam–Warnke [10] is chosen, in order to consider the important role of the intermediate principal stress in concrete materials and a non-associated flow rule is employed to control inelastic dilatancy. To model damage behaviour, the formulation based on total strain energy is adopted, in a format presented by Salari et al. [3].

Complex response phenomena of concrete materials (inelastic dilatancy, pressure sensitivity, etc.) are at the basis of specific failure characteristics and the formation of cracks and shear bands that are typical examples of localized failure mechanisms. Localization analysis in form of bifurcation studies of the localization tensor signals the formation of weak C^{-1} discontinuities in the velocity field synonymous with the loss of ellipticity.

Original works in this field are to be attributed to Rudnicki and Rice [11] and Rice and Rudnicki [12] for pressure-sensitive plasticity, based on original theories by Hadamard [13] and Hill [14] regarding bifurcation on stationary acceleration waves.

A number of authors investigated the bifurcation problem and developed algorithms for a variety of elasto-plastic concrete models, extending, in some cases, the results when considering also the presence of damage (Bigoni and Hueckel [15,16], Kang and Willam [17], Liebe and Willam [18], Rizzi et al. [19], Steinmann and Willam [20], Vrech and Etse [21], Willam and Iordache [22,23]).

Cosserat or micropolar continuum formulations [24] were introduced to incorporate gradients and length scales of the material microstructure within a consistent framework of continuous media. The general formulation was first introduced by Cosserat and Cosserat [25,26]. The elastoplastic Cosserat formulation was described by Willam et al. [27] and De Borst [28] and the localization analysis of this higher order continua was extensively discussed by Willam et al. [27]. Detailed information about Cosserat implementation and formulation for finite element analysis was presented in papers by Kondo [29].

2. Theoretical framework

In this section, the governing equations for the Boltzmann and Cosserat continua are presented. The theoretical background for elastoplastic material behaviour and damage-plasticity formulation is delineated. Menétrey–Willam [30] plasticity and damage, as a separate loading function, criteria are introduced and the coupling of damage and plasticity based on effective stresses is described.

2.1. Boltzmann continuum

In order to characterize the motion of a body, the equilibrium, the kinematic and the constitutive equations are considered.

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