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Computational homogenization of composites experiencing plasticity, cracking and debonding phenomena

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Abstract

Aim of the present paper is the development of a homogenization technique able to determine the overall mechanical response of composite materials taking into account the cracking and plastic behavior of its constituents and the decohesion process among them. A representative volume element of a composite material is studied. The plastic effects in the constituents are considered introducing a plastic model with isotropic and kinematic hardening. The debonding between constituents and the cracking process are described introducing a cohesive damage interface model that takes into account also the unilateral contact and frictional effects. In particular, a new procedure based on the nonuniform Transformation Field Analysis is presented. The plastic strains in the constituents and the inelastic relative displacements along the interfaces are approximated as linear combinations of inelastic scalar modes that are functions of the spatial variables. The coefficients of the linear combinations are the internal variables of the problem that are computed solving the evolutive problem. Some numerical applications are carried out to verify the efficiency of the proposed homogenization approach in reproducing the overall mechanical response of composites characterized by cracking and plastic phenomena in the constituents and debonding between them. The homogenization results are compared with the solution obtained by micro-mechanical nonlinear finite element analyses.

Keywords: Composite materials; Homogenization; Nonuniform TFA; Cracking; Plasticity; Debonding

1. Introduction

Composite materials are used in several fields of engineering applications. The development of new and innovative composite materials together with the enhancement of material models and of computational tools promoted the implementation of effective numerical procedures for the accomplishment of sophisticated and accurate stress analyses of composite structural elements. One of the main challenge in the structural analysis of elements made of composite materials is the implementation of reliable multiscale approaches [1,2]. The issue of the multiscale analysis is so actual in the world of the research that more than one scientific journal is completely dedicated to the field of multiscale computation.

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Several multiscale techniques have been proposed in the literature; they can be collected into two classes: uncoupled and coupled multiscale approaches [3]. The uncoupled approach is used when the structural scale and the material heterogeneity scale are very far; in this case, the homogenization technique is applied at the microscale to derive the overall constitutive response of the composite material to be used at the macroscale. On the contrary, when the size of the heterogeneities is not very far from the characteristic dimension of the structure, the uncoupled approach can fail and the homogenization cannot be fruitfully used. In this case, the full coupled multiscale analysis have to be performed. It is based on the superposition method and on the hierarchical decomposition of the solution space into global and local effects, enforcing the solution compatibility by prescribing suitable conditions at the global–local interface. As it can be easily argued, the coupled multiscale approach is much more complex and computationally expensive with respect to the uncoupled one, based on classical homogenization procedures; for this reason, if not strictly necessary, the uncoupled approach is preferred and, hence, widely used in literature.

When the constituents of the composite are subjected to significant nonlinear effects, analytical homogenization procedures could be ineffective and numerical homogenization techniques have to be adopted. In the last decade, with the increasing of the number of powerful CPU in the computers and the development of parallel codes, the FE^2 approach received great interest [4]. It consists in the use of finite element (FE) method both at the structural and at the material scales, leading to highly computational efforts.

Further computational homogenization techniques have been also developed to derive the nonlinear response of composite materials. In this framework, the Transformation Field Analysis (TFA) is an interesting technique able to account for the nonlinear response of the component materials, by means of the use of the coaction theory. Initially proposed by Dvorak [5,6], it has been adopted in an effective computational tool enhanced by Chaboche [7]. Michel and Suquet [8,9] proposed a deeply modified version of the TFA, based on the use of nonuniform distribution of the coactions, significantly improving his performances, as proved also in [10–12]. A different approach of the nonuniform TFA method has been proposed recently in [13], introducing a more general approximation of the inelastic fields and of the evolution procedures [14]. TFA approaches have been developed to derive the nonlinear response of composites whose components are characterized by different constitutive laws including plasticity, visco-elasticity, shape memory alloy model and also damage [15–23].

Indeed, one of the failure mechanism of composites is the detachment of the inclusion from the matrix. This phenomenon is concentrated along interfaces and leads to localized damage with possible restiffening due to unilateral contact and to frictional behavior. In fact, some difficulties can arise in the evaluation of the macroscopic constitutive response of heterogeneous materials when its constituents are characterized by cracking phenomena and when decohesion between the constituents occurs. This problem has been studied by Fritzen and Leuschner [24] who adopted the TFA approach to study elastic bulk materials with hyperelastic cohesive interfaces.

Aim of the present study is the development of a homogenization technique for composites able to derive the overall mechanical response of the material taking into account the cracking and plastic behavior of its constituents and the decohesion process between them. The main idea is to extend the nonuniform TFA homogenization procedure to the case of composites subjected to interface decohesion, unilateral contact, friction and plasticity effects.

In particular, a nonuniform distribution of the plastic strain in the constituents is taken into account. Each constituent is divided in sub-domains. In each sub-domain the plastic strain is approximated as a linear combination of solid inelastic modes that are scalar functions of the spatial coordinates. The coefficients in the linear combination are the internal variables that are computed during the evolution process. In particular, a plastic model with isotropic and kinematic hardening is adopted for the constituents of the composite materials.

The debonding between constituents and the cracking occurring in each constituent are modeled introducing a suitable interface model, as schematically represented in Fig. 1. A nonuniform distribution of inelastic relative displacement along the interfaces is taken into account. The interfaces are divided in sub-interfaces. The inelastic relative displacements along each sub-interface are approximated as linear combinations of inelastic modes that are scalar functions of the spatial coordinates. The coefficients of the linear combination are the internal variables that are determined during the evolution problem. An interface damage model is implemented in order to take into account the cracking occurring in the sub-domains and the decohesion phenomena between the constituents.

The plastic strains in the constituents and the inelastic relative displacements along the interfaces are evaluated developing a procedure to solve the evolution problem based on continuum evolution equations.

The proposed approach requires the computation of localization tensors and influence factors that are evaluated using linear finite element analyses.