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Effects of microfracture and contact induced instabilities on the macroscopic response of finitely deformed elastic composites

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A B S T R A C T

An original non-linear analysis of the homogenized response of periodic elastic composites under large deformations, is here carried out by accounting for the coupled effects of micro-cracks in unilateral self-contact and of instabilities and bifurcation microstructural phenomena. The structure and properties of the composite macroscopic response are investigated by obtaining new analytical results able to distinguish the contributions of microstructural heterogeneities, including fractures and voids, crack self-contact and local constitutive behavior. In light of these results the relations between microstructural instability mechanisms and macroscopic instabilities detected by loss of ellipticity or softening behavior of the homogenized tangent moduli tensor related to conjugated stress and strain rate measures, are studied. Novel numerical applications of the theory, developed by means of coupled FE models of a 2D microcracked composite with circular inclusions driven along uniaxial and biaxial macro-deformation paths, are presented pointing out the sequence of bifurcation and instability load factors for different micro-geometries and the relations among the stability domains at both micro and the macro levels.

1. Introduction

Owing to their high performances in comparison with conventional materials, heterogeneous materials, such as composite materials with particle-, fiber-reinforced or cellular microstructures and functionally graded materials, are widely adopted in various modern engineering applications and emerging technologies involving large deformations [1–6]. These applications include, for instance, thermoplastic multiphase polymers with rubber-like behavior adopted for rubber tires, shock absorber or flexible tubes, electroactive polymers used as actuators and sensors, magnetorheological elastomers used for damping components and vibration absorbers. Since their macroscopic mechanical properties can be tailored to meet specific requirements (e.g. increase in stiffness, strength, fracture toughness and durability) by an appropriate calibration of the microstructural geometrical and mechanical details, the relationships between the behaviors at the structural and the microscopic levels must be accurately evaluated.

Within the framework of small deformations, different approaches have been proposed in the literature to account for the effects of microstructural properties of composite materials, ranging from phenomenological modeling (including some recent nonlocal formulations [7–10] for describing the size-dependent mechanical behavior of functionally graded nanomaterials) to homogenization and multi-scale techniques, often assuming a periodic model for the micro-structure and adopting either a numerical (e.g. finite element) [11–15] or an analytical approach [16,17]. Generally speaking the homogenization approach may lead to strong approximations for locally periodic composites and when microscopic damage occurs since the assumptions of both periodicity and scale separations fail [18,19]. Consequently more general multiscale methods must be adopted, such as the concurrent, semi-concurrent, heterogeneous and asymptotic expansion ones (see Refs. [20–23], respectively).

For heterogeneous media under large deformations, several nonlinear features must be accounted to perform an analysis at the structural level able to accurately reflect the effects of microstructural evolution. Among these features, instability phenomena occurring at both the micro and macroscales (see, e.g. [24,25]) and arising from both geometrical and constitutive nonlinearities (see, for instance [26,27]), and microscopic fracture processes often involving self-contact between crack surfaces [28,29], exert a significant influence on the overall failure response of these materials.

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A detailed micromechanical approach, usually developed by using the finite element (FE) methodology, leads to increase the computational effort so much that an analysis at the structural level becomes unpractical from the engineering point of view. In fact a very fine solid FE discretization and a strongly nonlinear model are required to represent these physical processes. As a consequence, more effective methodologies must be adopted in order to incorporate the above nonlinear microscopic mechanisms into a macroscopic analysis of the composite system.

The influence of microstructural instability phenomena on the nonlinear effective response of heterogeneous materials subjected to large deformations has been widely studied in the literature from both the theoretical and numerical point of views [24,25,30–39].

In the framework of hyperelastic heterogeneous solids with periodic microstructure, an abstract formula for the homogenized energy density has been introduced in Ref. [40], requiring calculations performed over a representative volume element (RVE) composed by an a-priori unknown unit cells number since the energy minimizing microstructural buckling mode must be captured. In addition it has been proved that the homogenized energy density is not strictly rank-one convex at adequately high macroscopic strains, in spite this condition is satisfied for each microstructural constituents. This has pointed out the completely different nature of the macroscopic behavior of the solid with respect to that of its microscopic constituents. The interrelations between microscopic (also referred to as “local”) instabilities, repeating over a finite number of unit cells, and macroscopic ones, corresponding to the failure of rank-one convexity of the homogenized energy density, was firstly studied in Ref. [30] for layered composites. These connections were rigorously proved for a wider class of heterogeneous periodic materials by the subsequent work [31], where it was shown that long wavelength (also referred to as “global”) instabilities lead to the loss of rank-one convexity of the homogenized energy density and then to the loss of strong ellipticity condition for the unit cell homogenized moduli tensor, a situation indicating possible instabilities for the homogenized material. By using the Bloch wave methodology introduced in this work, according to which it suffices to consider all the possible functions periodic over a unit cell and the wave numbers in the appropriate Fourier space domain, several studies have been developed in order to investigate the onset of failure due to microscopic and macroscopic instabilities for several types of microstructures, such as layered composites, honeycomb and cellular solids (see, for instance [30,34,36,39]). Except in the case of global instability modes, for which the onset of such instability can be simply detected by the loss of strong ellipticity of the one-cell homogenized moduli tensor, the determination of the onset of microscopic instabilities of local type is a difficult task often requiring prohibitive time-consuming computations due to the theoretically infinite nature of the analysis domain, in both the case of Bloch wave stability calculations and of direct finite element discretization of the unit cell assembly. Unfortunately the macroscopic stability prediction provides overestimation of the real microscopic stability region, since the heterogeneous material may become unstable before reaching the failure surface defined by the loss of strong ellipticity of the one-cell homogenized moduli tensor. Therefore in several practical applications, local instability modes with a finite wavelength need to be determined. In light of this the possibility to obtain a conservative prediction of the microscopic stability region by adopting alternative macroscopic constitutive stability measures has been investigated [25,37].

In addition using computational homogenization approaches similar to those formulated within the small deformations theory (see Refs. [12,41], for instance), multilevel finite element techniques have been also adopted to perform double scale analysis of long fiber reinforced composites by coupling instabilities at the microscopic level with an analysis at the macroscopic level and adopting two nested continuum models exclusively based on the local constitutive behavior [35,42].

In spite of the above referred large amount of investigations addressing microscopic instability phenomena, the problem of interaction between instabilities and microfracture phenomena, is a mechanism of failure for composite materials undergoing large deformations not adequately studied in the literature. Yet microscopic fractures, usually involving self-contact between crack faces, may trigger microstructural instability phenomena leading to a premature failure of the heterogeneous solid [43]. Moreover, microstructural buckling may lead to a sudden increase of energy release rate at the tips of micro-cracks and to the subsequent propagation of existing defects [44]. To this end this paper, starting from previous authors' results obtained in Refs. [29,43], attempts to give a contribution towards a better understanding of microfracture induced instability failure mechanisms, which can be of crucial importance for a successful design of heterogeneous material systems. Firstly the RVE microscopic problem is formulated by taking into account configuration dependent incremental loading arising from crack self-contact and the related stability and non-bifurcation conditions are discussed. Consequently, the analytical structure of the macroscopic constitutive solid response is analyzed by also pointing out its main properties. Then macroscopic instability conditions based on the softening behavior of the homogenized tangent moduli tensor defined for a class of conjugated stress and strain rate measures, are formulated and their links with microstructural instability mechanisms and with the loss of macroscopic ellipticity are studied. Novel numerical examples, developed by means of a coupled FE approach, are proposed in order to apply the above theoretical results and to establish the effects of microfracture and contact induced instabilities on the onset of macroscopic instabilities.

2. Problem statement

Consider a representative volume element (RVE) of a composite material associated with a periodic microstructure and occupying the volume $V_{(i)} \subset \Re^3$ (with boundary $\partial V_{(i)}$) in the undeformed reference configuration (Fig. 1). The RVE consists of a solid part $B_{(i)}$, a void part, denoted by $H_{(i)}$, and contains cracks whose upper and lower surfaces, respectively denoted as $\Gamma^u_{(i)}$ and $\Gamma^l_{(i)}$, may be subjected to frictionless self-contact. The nonlinear deformation of the micro-structure $\boldsymbol{x}$ ($\boldsymbol{X}$) maps a material point $\boldsymbol{X}$ of $V_{(i)}$ to a new position defined by $\boldsymbol{x}$ in the deformed configuration V of the RVE. The deformation is then characterized by the deformation gradient $\boldsymbol{F} = \partial\boldsymbol{x}(\boldsymbol{X})/\partial\boldsymbol{X}$ and the constitutive behavior of each microstructural constituents is assumed to be expressed by an incremental linear relationship between the deformation gradient rate $\dot{\boldsymbol{F}}$ and the first Piola-Kirchhoff stress rate tensor $\dot{\boldsymbol{T}}_R$. Introducing the fourth-order tensor of nominal moduli $\boldsymbol{C}^R$, assumed to satisfy the major symmetry condition, the constitutive law can be thus expressed as:

$$\dot{\boldsymbol{T}}_R = \boldsymbol{C}^R(\boldsymbol{X},\boldsymbol{F})[\dot{\boldsymbol{F}}], \qquad (1)$$

which is representative of a wide class of rate-independent materials, including hyperelastic ones as a particular case. We are interested in the response of the heterogeneous solid to quasi-static loading programs defined as a function of the time-like parameter $t \geq 0$ ($t = 0$ corresponding to the reference undeformed configuration) and especially in its incremental (or rate) response. To this