Micromechanical Modeling of Brittle Damage in Composite Materials: Primary Anisotropy, Induced Anisotropy and Opening-Closure Effects

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ABSTRACT

Inelastic deformation of various brittle materials such as concrete, rocks or composites has been widely explained by the existence, nucleation and growth of microcracks. The oriented nature of these microdefects, coupled with the unilateral contact of their lips (i.e. microcracks can be either open or closed depending on loading), leads to a complex anisotropic behaviour notably characterized by a recovery of some effective properties at the closure of microcracks.

For composite materials, the interaction of these both features with their primary (structural) anisotropy makes things even more complex. Experimental investigations through ultrasonic measures on ceramic matrix composites confirm the stiffness modifications due to degradation process, both on the amplitude (when loading axes correspond to initial material axes) and on the type of resulting material symmetry, especially in the case of off-axis loadings [3]. Concerning the unilateral effect, some authors have put in evidence the partial recovery of elastic properties at the closure of microcracks but these studies are often restricted to axial properties or to defects configurations coinciding with to the structural anisotropy of the material [1,8].

In terms of representation, the simultaneous description of the damage induced anisotropy and of the activation-deactivation process (the so-called unilateral effect) within a consistent modeling still remains a difficult and open research field, even in the context of initially isotropic materials. Indeed, mathematical or thermodynamical inconsistencies have been pointed out in existing formulations, such as discontinuities of the stress-strain response or non-uniqueness of the thermodynamic potential [4-5]. Concerning anisotropic microcracked materials, the analysis of their overall elastic properties is limited to configurations of open defects [6,7,9].

This paper aims to introduce a novel and original modeling approach for this problem within the framework of Continuum Damage Mechanics. In view of the lack of exhaustive experimental data on such aspects, we propose a micromechanics-based formulation of the resulting -generally fully- anisotropic multilinear response of orthotropic materials containing microcracks. On the basis of works by [2] for isotropic media, a strain-based homogenization approach is developed. This leads to a closed-form expression of the macroscopic free energy corresponding to 2D initially orthotropic materials weakened by arbitrarily oriented microcrack systems with account of closure effects. The consideration of such unilateral

behavior constitutes one of the main contribution of the study. The explicit expressions obtained provide then a complete quantification of interaction effects both between primary and microcracks-induced anisotropies and between opening/closure states of cracks on the materials elastic properties.

The thermodynamics framework finally gives a standard procedure for the formulation of the damage evolution law that ensures in all cases the verification of the thermodynamics second principle. Moreover, the association of the overall free energy expression derived with the standard evolution law introduces both oriented and closure effects due to microcracks in the material response and damage evolution. The model has been implemented within the finite-element code ABAQUS and various numerical simulations illustrate the representation capacities. Indeed, the formulation can account for the main features of brittle cracking kinetics, especially the load-induced anisotropy and the dissymmetry between initial damage thresholds in tension and compression.

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