Available online at www.sciencedirect.com
ScienceDirect
Comput. Methods Appl. Mech. Engrg. 294 (2015) 384–427
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Continuum approach to computational multiscale modeling of propagating fracture

J. Oliver[a,b,*], M. Caicedo[b], E. Roubin[b], A.E. Huespe[b,c], J.A. Hernández[a,b]

[a] *E.T.S. d'Enginyers de Camins, Canals i Ports, Technical University of Catalonia (BarcelonaTech), Spain*
[b] *Centre Internacional de Metodes Numerics en Enyinyeria (CIMNE), Campus Nord UPC, Edifici C-1, c/Jordi Girona 1-3, 08034 Barcelona, Spain*
[c] *CIMEC-UNL-CONICET, Güemes 3450, Santa Fe, Argentina*

Available online 9 July 2015

Abstract

A new approach to two-scale modeling of propagating fracture, based on computational homogenization (FE^2), is presented. The specific features of the approach are: (a) a continuum setting for representation of the fracture at both scales based on the Continuum Strong Discontinuity Approach (CSDA), and (b) the use, for the considered non-smooth (discontinuous) problem, of the same computational homogenization framework than for classical smooth cases. As a key issue, the approach retrieves a characteristic length computed at the lower scale, which is exported to the upper one and used therein as a regularization parameter for a propagating strong discontinuity kinematics. This guarantees the correct transfer of fracture energy between scales and the proper dissipation at the upper scale. Representative simulations show that the resulting formulation provides consistent results, which are objective with respect to size and bias of the upper-scale mesh, and with respect to the size of the lower-scale RVE/failure cell, as well as the capability to model propagating cracks at the upper scale, in combination with crack-path-field and strain injection techniques. The continuum character of the approach confers to the formulation a minimal intrusive character, with respect to standard procedures for multi-scale computational homogenization.

Keywords: Multi-scale; Fracture; Propagating failure; Continuum Strong Discontinuity Approach (CSDA)

1. Introduction

Multi-scale computational modeling of solids, aiming at improving the predictive capabilities of mechanical models accounting for the description of the material at several scales, is a subject of increasing interest. A number of analytical and computational strategies have been developed in the past considering the description of the constitutive material at different scales, [1–14]. In most of them, multiscale description of the material itself

* Corresponding author at: E.T.S. d'Enginyers de Camins, Canals i Ports, Technical University of Catalonia (BarcelonaTech), Spain.
E-mail addresses: xavier.oliver@upc.edu (J. Oliver), mcaicedo@cimne.upc.edu (M. Caicedo), eroubin@cimne.upc.edu (E. Roubin), ahuespe@intec.unl.edu.ar (A.E. Huespe), jhortega@cimne.upc.edu (J.A. Hernández).

http://dx.doi.org/10.1016/j.cma.2015.05.012
0045-7825/

(e.g. computational material homogenization) and consequences and implications, on the overall modeling of the solid, of this specific description (computational multiscale modeling), are not generally considered in an integrated setting. In the context of a two scale (macro scale–micro/meso-scale) problem, computational homogenization of materials (FE^2) is generally regarded as a way of replacing, at the structural-scale, standard stress–strain phenomenological constitutive models equipped with internal variables, accounting for the micro/mesoscopic material morphology, by point wise overall stress–strain evaluations. The overall stresses are then obtained after solving an auxiliary problem, *the homogenization problem*, at the micro/meso-scale, in a manifold, the Representative Volume Element (RVE), endowed with a geometrical description of the material morphology. In turn, this RVE problem relies on some well-established paradigms, typically the classical Hill–Mandel principle [1,14,15] and the strain and stress homogenization concepts. More specifically: in this work we consider as starting point the modern *variational approach to multiscale homogenization* [16,17]. After this, the structural modeling proceeds at the macro/structural scale in a standard manner, with no further modifications.

This weak coupling makes sense for problems involving smooth – linear or nonlinear – material behavior, but the issue seems not to be so clear for non-smooth responses, like *material failure*, – typically fracture, de-cohesion, shear banding etc. – where the involved entities (strains, stresses, displacements) can be non-smooth or even unbounded [18]. For these non-smooth problems, two options emerge:

(a) Use the same homogenization paradigms than for smooth problems, with no specific modification. This approach has been strongly objected: even the existence of the RVE can be questioned, arguing that for fracture cases the material loses the statistical homogeneity [19], or, from another point of view, that the homogenized constitutive model lacks an internal length [20]. A crucial consequence of this issue is the lack of objectivity of the results with respect to the size of the RVE.
(b) Modify the homogenization paradigm towards a specific one for non-smooth problems. Selective RVE domain homogenization methods [21–25] or specific new homogenization paradigms [26,27] are possible ways to retrieve RVE-size objectivity of the results. However, sometimes this is done at the cost of a much higher complexity and intrusion in existing codes and loss of generality of the approach.

In this context, this work presents a new approach for computational multiscale analysis in non-smooth problems with the following features:

1. Extends the homogenization paradigms for smooth problems – typically the Hill–Mandel principle and the stress–strain homogenization procedures – to non-smooth problems, with no fundamental changes.
2. In both scales, a continuum (stress–strain) constitutive relationship is considered, instead of the most common discrete traction/separation-law, this contributing to provide a unified setting for smooth and non-smooth problems. This is achieved by resorting to the well-established Continuum Strong Discontinuity Approach (CSDA) to material failure [28,29,18].
3. As for the multiscale modeling issue, it involves a crucial additional entity: *a characteristic length*, which is point wise obtained from the geometrical features of the failure mechanism developed at the low scale. Introduction of a characteristic length in material homogenization schemes has been claimed as an ineluctable requirement for physical consistency [20], and some approaches to this subject can be found in recent works [30]. As a specific feature of the presented approach, for the non-smooth case this characteristic length is exported, in addition to the homogenized stresses and the tangent constitutive operator, to the macro-scale, and *considered the bandwidth of a propagating strain localization band, at that scale*.
4. Consistently with this characteristic length, a specific computational procedure, based on the *crack-path-field and strain injection techniques*, recently developed by the authors [31], is then used for modeling the onset and propagation of this localization band, at the macro-scale. This ensures the macro-scale mesh-size and micro-scale RVE-size objectivity of the results, and the proper energy dissipation at both scales.

In the remaining of this work a detailed description of the mechanical and computational elements of the proposed approach is presented. In Section 2, the multi-scale framework and the corresponding homogenization procedure, are described, whereas in Section 3 material failure propagation issues are addressed. Section 4 is devoted to present some representative numerical simulations to assess the performance of the proposed approach, and finally, in Section 5, some concluding remarks are stated.

Not to distract the reader's attention on issues that, though being crucial for the completeness of the work and the reproducibility of the results, are not in the core of the proposed approach, some appendices are added at the end of the