Accepted Manuscript

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PII: S0045-7825(16)31788-1
DOI: http://dx.doi.org/10.1016/j.cma.2017.04.025
Reference: CMA 11427

To appear in: *Comput. Methods Appl. Mech. Engrg.*

Received date : 12 December 2016
Revised date : 19 April 2017
Accepted date : 22 April 2017

The composite voxel technique for inelastic problems

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Abstract

The composite voxel technique was developed in the framework of linear elasticity and hyperelasticity for regular voxel grid descretizations which can not resolve material interfaces exactly in general. In this work, we study the inelastic behavior of two-phase laminates. In particular, we derive an analytical nonlinear formula for the unknown rank one jump of the strain across the interface. This enables us to extend the composite voxel technique to account for inelastic material behavior at small strains.
We demonstrate by numerical experiments on continuously and discontinuously reinforced thermoplastics with elastoplastic matrix behavior that FFT-based computational homogenization on downsampled microstructures equipped with composite voxels produces stress-strain curves mimicking those obtained for the full resolution. For industrial sized microstructures it turns out that the computations can be accelerated by a factor of up to 40 compared to a direct parallelisation of the fully resolved problem.

Keywords: Nonlinear composites, Homogenization, Lippmann-Schwinger equation, FFT
2010 MSC: 74B05, 74S25, 74E30, 74M25, 45A05, 65T50

1. Introduction

The output format of modern large scale image acquisition techniques like micro-computed tomography has fostered research on numerical methods which operate directly on pixel or voxel data, i.e. regular Cartesian grids. These so-called data-driven numerical methods exploit the regular structure of the mesh to derive fast solution methods with low memory requirements.
Still, the resolution of state-of-the-art tomography poses challenges for the numerics. A single double precision scalar field on a 4096^3 voxel image, which most μCT scanners can produce, occupies already 512 GB of memory. Thus, even performing linear elastic computations on such images requires the use of either a very powerful workstation or a computing cluster, not to mention inelastic computations, where a number of history variables needs to be stored, increasing the memory demand significantly.
To enable computations on conventional desktop computers or workstations still taking into account the microstructural detail of the fully resolved image the composite voxel technique was developed for linear elastic and hyperelastic problems [1, 2, 3]. A coarse graining procedure serves as the initial idea, i.e. a number of smaller, typically $4^3 = 64$, voxels are merged into bigger voxels. Each of these so-called composite voxels gets assigned an appropriately chosen material law which is based on a two-phase laminate incorporating more accurate volume fractions and an approximated interface normal n, reflecting the microstructural features.
This article is organized as follows: In section 2 we derive an explicit formula for the rank-one jump $a \otimes_s n$ of the strains of nonlinear elastic two-phase laminates (see equation (2.13)), which is solved in section 3.1 by the Newton-Raphson method for the jump a, cf. Algorithm 2. Then in section 4 the solution quality for these laminate composite voxels are compared to trivial downsampling (use the dominating phase) and volume averaging of the stress responses of the constituents (called Voigt averaging). Finally, in section 4.5 we assess the computational efficiency of the composite voxel approach for a complex fiber reinforced microstructure.

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