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Plastic strain heterogeneity in composite materials and the Nonuniform Transformation Field Analysis

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Abstract :

The Nonuniform Transformation Field Analysis is a reduced order model for the effective behavior of nonlinear composite materials. It is based on the decomposition of the plastic strain field on nonuniform plastic modes. It is presented and applied to the modeling of the aging behavior of a nuclear fuel.

Keywords : Homogenization. Composites. Viscoplasticity. Reduced Order Model.

1 Motivation

Homogenization of composites or heterogeneous materials with nonlinear constituents is a long-standing problem. It is well recognized that the nonlinearity introduces a strong coupling between the different scales which, in full rigor, remain coupled. This observation has motivated the development of coupled, full-field, multi-scale methods (such as the FEM² method of [2]). However the cost of these methods is still prohibitive for full-scale simulations of structural problems and has motivated the development of reduced order models (ROM) achieving a good compromise between accuracy and efficiency. A typical example of such a ROM is the Transformation Field Analysis ([1]). However some of the characteristic features of the plastic strain fields are not well captured by the TFA, which assumes that the plastic strain field is uniform in individual phases or in subdomains of each individual phase.

The Nonuniform Transformation Field Analysis ([3]) extends on the TFA. It is not only motivated by the need of cutting down the costs of structural analyses at the macroscopic scale by working with a reduced-order model, but it also accounts in a more satisfactory way for the local characteristics of the microscopic strain fields observed in nonlinear composites. Indeed, two striking features of these local fields, revealed either experimentally or through numerical simulations, are first their *strong nonuniformity in space*, even within individual constituents, and second a strong *patterning effect* (or self-organization) of the fields into zones where the plastic strain concentrates and zones which are left nearly undeformed.

2 The NTFA constitutive model

In the NTFA the field of (visco)plastic strains is decomposed on a set of *plastic modes*, $\boldsymbol{\mu}^{(k)}$:

$$\boldsymbol{\varepsilon}^{\text{vp}}(\boldsymbol{x}, t) = \sum_{k=1}^M \varepsilon_k^{\text{vp}}(t) \boldsymbol{\mu}^{(k)}(\boldsymbol{x}). \quad (1)$$

Unlike in the classical transformation field analysis, the modes $\boldsymbol{\mu}^{(k)}$ depend on the spatial variable \boldsymbol{x} . The local stress and strain fields in a single volume element can be expressed as:

$$\boldsymbol{\varepsilon}(\boldsymbol{x}, t) = \boldsymbol{A}(\boldsymbol{x}) : \bar{\boldsymbol{\varepsilon}}(t) + \sum_{k=1}^M \boldsymbol{\eta}^{(k)}(\boldsymbol{x}) \varepsilon_k^{\text{vp}}(t), \quad \boldsymbol{\sigma}(\boldsymbol{x}, t) = \boldsymbol{L}(\boldsymbol{x}) : \boldsymbol{A}(\boldsymbol{x}) : \bar{\boldsymbol{\varepsilon}}(t) + \sum_{k=1}^M \boldsymbol{\rho}^{(k)}(\boldsymbol{x}) \varepsilon_k^{\text{vp}}(t), \quad (2)$$

where

$$\boldsymbol{\eta}^{(k)}(\boldsymbol{x}) = \boldsymbol{D} * \boldsymbol{\mu}^{(k)}(\boldsymbol{x}), \quad \boldsymbol{\rho}^{(k)}(\boldsymbol{x}) = \boldsymbol{L}(\boldsymbol{x}) : \left(\boldsymbol{\eta}^{(k)}(\boldsymbol{x}) - \boldsymbol{\mu}^{(k)}(\boldsymbol{x}) \right), \quad (3)$$

\boldsymbol{D} is the nonlocal elastic Green's operator which gives the strain at point \boldsymbol{x} due to the presence of an eigenstrain $\boldsymbol{\mu}^{(\ell)}(\boldsymbol{x}')$ at point \boldsymbol{x}' , the average strain $\bar{\boldsymbol{\varepsilon}}$ being zero.

The model involves two different steps, where choices have to be made with consequences on the cost/accuracy of the resulting model:

1. *Choice of the plastic modes.* The modes are chosen to have their support in a given phase. Their selection is performed by the Karhunen-Loève decomposition from pre-computed snapshots. The method has similarities, but also differences, with POD (Proper Orthogonal Decomposition) methods.
2. *Evolution equations for the generalized plastic components ε_{ℓ}^{VP} 's.*

As an example, the results of a recent study on creep of mixed oxides (MoX), a nuclear fuel which is typically a three-phase composite, will be presented. The individual constituents of MoX are viscoelastic but undergo aging under irradiation. The NTFA model accounts for aging effects even with modes identified with the non-aged material properties of the constituents. It is found that not only the global response of the composite, but also the local fields statistics obtained by the localization rule (1), (2) and (3), are well captured by the model (see figure 1, right).

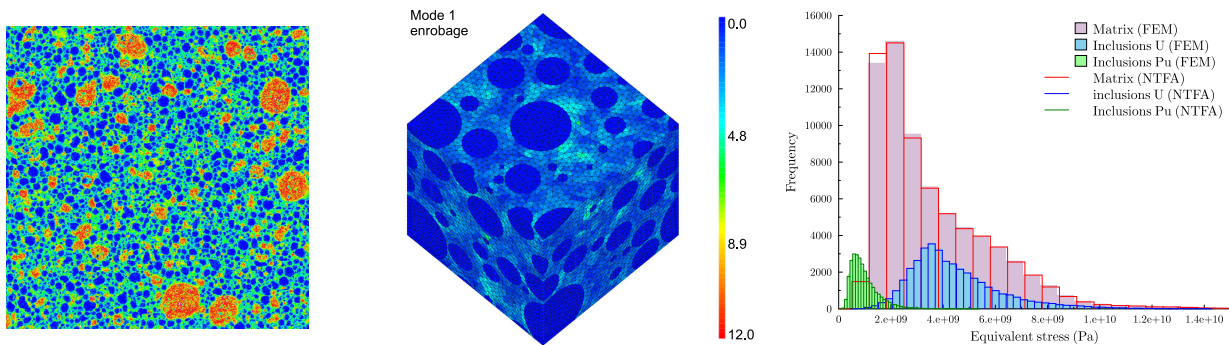


Figure 1: Mixed oxide nuclear fuel. Left: micrograph showing the 3 constituents (red, blue and green). Center: plastic mode 1 in the matrix phase. Right: probability distribution of the stress in the three constituents.

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