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Numerical homogenization of concrete microstructures without explicit meshes

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ABSTRACT

Life management of electric hydro or nuclear power plants requires to estimate long-term concrete properties on facilities, for obvious safety and serviceability reasons. Decades-old structures are foreseen to be operational for several more decades. As a large number of different concrete formulations are found in EDF facilities, empirical models based on many experiments cannot be an option for a large fleet of power plant buildings. To build predictive models, homogenization techniques offer an appealing alternative. To properly upscale creep, especially at long term, a rather precise description of the microstructure is required. However, the complexity of the morphology of concrete poses several challenges. In particular, concrete is formulated to maximize the packing density of the granular skeleton, leading to aggregates spanning several length scales with small inter particle spacings. Thus, explicit meshing of realistic concrete microstructures is either out of reach of current meshing algorithms or would produce a number of degrees of freedom far higher than the current generic FEM codes capabilities.

This paper proposes a method to deal with complex matrix-inclusions microstructures such as the ones encountered at the mortar or concrete scales, without explicitly meshing them. The microstructure is superimposed to an independent mesh, which is a regular Cartesian grid. This inevitably yields so called “gray elements”, spanning across multiple phases. As the reliability of the estimate of the effective properties highly depends on the behavior affected to these gray elements, special attention is paid to them. As far as the question of the solvers is concerned, generic FEM codes are found to lack efficiency: they cannot reach high enough levels of discretization with classical free meshes, and they do not take advantage of the regular structure of the mesh. Thus, a specific finite differences/finite volumes solver has been developed. At first, generic off-the-shelf linear system solvers were used. To further improve the efficiency in terms of memory requirements, specific variants of the preconditioned conjugate gradient were implemented. This allowed to homogenize the conductivity of a concrete-like microstructure using more than 10^9 degrees of freedom on a rather common hardware for 2010 (a PC embedding 48 GB of RAM). Taking benefit of the properties of the regular Cartesian grid we have also investigated a multi-level method to improve the CPU efficiency of the code.

1. Effective creep estimation: does stiffness contrast matter?

To estimate the effective creep function of a composite made up of several non aging linear visco-elastic phases, the correspondence principle is classically used [11]. Indeed, the Laplace–Carson transform changes the structure of a visco-elastic behavior into an elastic one. This allows to take advantage of homogenization models developed in the framework of linear elasticity. The effective creep function is thus obtained in the Laplace domain. The last step is to revert into the physical time domain, inverting the Laplace transform. Unfortunately, except for very simple elementary visco-elastic behaviors and elastic homogenization models, this inversion is not analytically tractable. A numerical inversion procedure is thus required, such as for example [10,19] the truncated series expansion:

$$f(t)\approx\frac{\ln 2}{t}\sum_{k=1}^{2M}\xi_k\mathcal{L}_f\left(\frac{k\ln 2}{t}\right) \tag{1}$$

$\mathcal{L}_f$ denoting the known Laplace transform of f, M being a sufficiently large integer (typically $M=10$ is found to be enough), and ξ_k being appropriate weights [10,19].

For pedagogic purposes, let us consider the upscalling of mortar creep to estimate concrete creep. To keep things analytically tractable, concrete morphology is modeled resorting to a Mori–Tanaka scheme [16]. The mortar behavior is represented by an isotropic Burgers model (Fig. 1), with different stiffness and viscous properties for spherical and deviatoric loadings, and the aggregates are assumed to be elastic. The mechanical characteristics of mortar and aggregates, come from [15] and are reported into Table 1. The aggregates volume fraction

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