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ScienceDirect
Comput. Methods Appl. Mech. Engrg. 328 (2018) 26–46
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

An adaptive concurrent multiscale model for concrete based on coupling finite elements

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Received 13 April 2017; received in revised form 26 July 2017; accepted 29 August 2017
Available online 7 September 2017

Abstract

A new adaptive concurrent multiscale approach for modeling concrete that contemplates two well separated scales (represented by two different meshes) is proposed in this paper. The macroscale stress distribution is used as an indicator to identify critical regions (where the material is prone to degrade) with the explicit aim to enrich these zones with detailed mesoscale material information comprising three basic phases: coarse aggregates, mortar matrix and interfacial transition zone. Thus, the concrete initially idealized as a homogeneous material is gradually replaced and enhanced by a heterogeneous multiphase one. This technique is particularly powerful to handle cases where the region with nonlinear behavior is not easy to anticipate. Furthermore, the proposed approach does not require the definition of a periodic cell (or a RVE), and the meshes from distinct scales are totally independent. The new adaptive mesh technique is based on the use of coupling finite elements to enforce the continuity of displacements between the non-matching meshes associated with the two different scales of analysis. Besides that, mesh fragmentation concepts are incorporated to simulate the crack formation and propagation at the mesoscopic scale, without the need of defining complex and CPU-time demanding crack-tracking algorithms. The strategy is developed integrally within the framework of continuum mechanics, which represents an advantage with respect to other approaches based on discrete traction/separation-law. Numerical examples with complex crack patterns are conducted to validate the proposed multiscale approach. Furthermore, the efficiency and accuracy of the novel technique are compared against full mesoscale and standard concurrent multiscale models, showing excellent results.

Keywords: Concrete; Concurrent multiscale model; Coupling finite element; Interface element; Continuum damage model; Crack propagation

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http://dx.doi.org/10.1016/j.cma.2017.08.048
0045-7825/

1. Introduction

The process of initiation and propagation of cracks in heterogeneous materials like concrete is a multiscale phenomenon. The local damage on a structural member is the result of physical processes occurring at a lower scale, identified hereafter as the mesoscale that involves: coarse aggregates, mortar matrix and an interfacial transition zone (ITZ). This multiphase meso-level dictates the fracture properties of the material. The properties of the individual mesoscale components (and their mutual interactions) play a critical role in the crack formation and subsequent propagation, as well as in the global mechanical behavior of the concrete [1,2]. In spite of some satisfactory results obtained with macroscopic constitutive models, it seems they are not the best option to assist a reliable understanding of this problem. The main drawback associated with macroscopic models is related to their limitations to include the effects of the mesoscale in the macroscopic response.

The use of multiscale models has been gaining progressively more prominence, particularly when trying to understand better the material trans-scale failure phenomenon [3–13]. In these models, the macroscopic problem is mainly controlled by the mechanical behavior of the material structure (e.g. the degradation of the micro and meso constituents is translated into loss of stiffness and energy dissipation). Hierarchical and concurrent multiscale approaches have been successfully used to model the nonlinear behavior of concrete structures [14]. These methods were initially based on two main concepts: scale separation and representative volume element (RVE) [15–20]. Distinct scale models are sequentially coupled in a continuous interaction between them. Two interacting processes are generally involved in this type of analysis: (i) the localization process, in which the coarser-scale response is transferred to the finer-scale material model to evaluate the behavior of the material structure, and (ii) the homogenization process, where the information from the finer structure is upscaled (to feed the constitutive equations related to the coarser-scale), to solve the macroscale problem [21]. This interaction characterizes the trans-scale process, where the nonlinear behavior occurring in the finer-scale controls the coarser-scale response, at the same time the boundary conditions at the macroscale affect the failure process taking place at the finer-scale. Usually this technique is known as FE^2 multiscale method because there is a finite element (FE) model inside another FE model [22]. Therefore, for each integration point of the macroscopic (global) FE mesh, a RVE analysis is conducted, and the homogenized response is returned up to the macroscale model.

One of the main challenges associated with the FE modeling of heterogeneous materials (e.g. concrete) incorporating mesoscale effects is to accurately represent the internal material structure using the current computer power. For example, analyses involving small concrete specimens (i.e. reduce scale experiments or similar), have been conducted based on a purely mesoscale approach to represent the material structure [2,23–27]. The excellent results obtained in these studies show that mesoscopic models are very useful for studying the influence of the concrete internal-structure (i.e. coarse aggregates, mortar matrix and the ITZ) on the macroscopic response. However, the very fine mesh necessary to conduct this type of analysis increases dramatically the computational effort (i.e. CPU time and memory requirements), which makes practically prohibitive the modeling of engineering problems using a pure mesoscale approach.

In the concurrent multiscale model the structure is generally divided into two main subdomains: (i) "critical" zones (i.e. regions where inelastic processes are anticipated), and (ii) "undamage" zones. The explicit representation of the concrete mesoscale circumscribes to those sub-domains where the nonlinear behavior is expected (i.e. critical regions). Both scales are solved simultaneously, resulting in a strong coupling between them [17,28,14]. An advantage of this method is that the definition of a RVE is not necessary. However, an efficient scheme to couple the non-matching meshes is needed to enforce global equilibrium and displacements compatibility between the subdomains, aspect that can be very challenging. Another advantage of this kind of approach is that the failure of the material can be explicitly simulated. Furthermore, accurate results in terms of both, crack initiation and propagation can be achieved. However, as pointed out by [17], the subdomains not only differ in terms of mesh refinement (i.e. a much finer mesh is required to represent the mesoscale), but also in terms of constitutive modeling (i.e. the behavior of each phase of the proposed material needs to be properly reproduced).

The finer-scale subdomains in concurrent multiscale models can be defined a priori to reduce the numerical effort and memory demand. These models are called explicit direct multiscale models and the most difficult task is to anticipate the regions that will present a nonlinear behavior to introduce there the refined scale mesh. To circumvent this problem, a number of adaptive multiscale models have been proposed [25,29–33]. In these models, the finer-scale region is not pre-defined but incorporated during the nonlinear simulation. The adaptive schemes are not new and they are not restricted to multiscale techniques. Mesh adaptation procedures, for example the *h*-*p*-adaptation method, has