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Adaptive image-based method for integrated multi-scale modeling of damage evolution in heterogeneous concrete

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ABSTRACT

This paper presents a new adaptive image-based method for integrated multi-scale modeling and computational approach to simulate the trans-scale process of dynamic fracture in concrete structures from evolving meso-damage to structural failure. Two numerical examples are presented to demonstrate the accuracy and effectiveness of the approach. The results show that, the approach can be used to reveal the dynamic fracture mechanisms of concrete structures by considering the trans-scale coupling process from meso-damage to local failure in vulnerable area and eventually to structural failure; and it can obtain satisfactory results with sufficient precision and lower cost, especially for large scale computations.

1. Introduction

Studying on failure mechanism of engineering structures has become the current important issue. It is observed that the failure of structure involves many coupled spatial scales [1–3]. And some disordered details in meso-scale can be amplified strongly due to trans-scale coupling and have a strong effects on the structural failure [4]. Therefore, the analysis on material behavior in the meso-scale plays an important role in understanding the failure mechanism of engineering structures. And some previous works have tried to study the failure mechanisms of structures from material damage evolution in meso-scale [5,6], especially for concrete which is widely used in engineering fields [7].

Concrete is usually considered to be a three-phase heterogeneous material that consists of aggregates, matrix material and the interfacial transition zone (ITZ) in meso-level [8–10]. And the material behavior of concrete is strongly related to the disordered meso-components [7]. In order to better understand the material behavior of concrete, it is necessary to be studied from the meso-scale point of view [11]. An effective method to analyze such a heterogeneous material requires a numerical model, which represents its individual heterogeneous meso-components, e.g. the shape and the spatial distribution of the aggregates [12]. However, there is a paucity of image-based models that consider the real heterogeneous material structural morphology in small scale [6]. For considering concrete meso-components, the main method is that the random geometrical configurations of the aggregate particles can be automatically generated based on the basic statistical characteristics of meso-components [13]. Wang et al. have generated rounded and angular aggregate based on Monte Carol random sampling principle [14]. Bazant et al. [15], Schlangen and van Mier [16] assumed that aggregate particles have spherical shapes. Leite et al. have developed a new stochastic-heuristic algorithm for obtaining ellipsoid aggregate particles with different shape and size distributions [17,18]. Although the random aggregate structure obtained from the previous methods based on the statistical sense can resemble the general distribution law of concrete meso-components, this cannot reflect the real individual material characteristics within special concrete sample. Meanwhile, the real meso-structural morphology have a significant influence on the stress distribution within the material and, therefore, on the initiation and accumulation of micro-cracks up to the macro-scale fracture [12]. So, in order to simulate the trans-scale process of dynamic fracture in concrete accurately, numerical model representing the real meso-structural morphology and non-uniformities should first be established.

Due to the large demand of memory capability and complexity of the numerical model, the pure meso-scale simulations are generally limited to small specimens [7]. For studying the failure mechanism of structures, especially for large scale engineering structures, pure macroscopic analysis is the usual way, in which concrete is considered as homogeneous material, such as by Scotta [19], Tang [20] and Faleiro [21]. Although this can obtain good

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macroscopic nonlinear mechanical behavior of concrete structures due to the initiation, growth, and coalescence of micro-cracks with low computational cost by adjusting model parameters, it does not explain their failure mechanisms from meso-scale. So, pure macro- or meso-scale analysis cannot be used to study failure mechanisms of large scale concrete structures from the meso-scale point of view due to their own characteristics. The need for multi-scale methods is realized for these problems, such as the computational homogenization scheme which is probably one of the most accurate techniques in up-scaling the nonlinear behavior of a well-characterized microstructure [22]. Kouzsnetsova, Geers, and Brekelmans developed a novel second-order computational homogenization procedure, which is suitable for a multi-scale modeling of macroscopic localization and size effects [23]. Hain and Wriggers used multi-scale model with computational homogenization method to obtain micro-structural investigations based on computer-tomography scans at micro-scale [24].

In order to simulate trans-scale process of dynamic fracture in concrete structures from meso- to macro-scale damage and eventually to structural failure with sufficient precision and lower cost, a new adaptive image-based method for multi-scale modeling and computational approach is developed in the present paper. In the multi-scale computational model, the macroscopic analysis in regions of low gradients and homogeneity incorporates homogenization-based continuum damage models for meeting the macroscopic mechanical behavior, while mesoscopic analysis in regions of high gradients due to damage where homogenization breaks down, incorporates image-based models for describing the real heterogeneous material meso-components. Meanwhile, the mesoscopic analysis regions can also meet the macroscopic mechanical behavior by adjusting model parameters of meso-components. An appropriate adaptive scale change criterion is developed to incorporate continuous changes in the integrated multi-scale modeling as a consequence of evolving damage, for improving the accuracy and efficiency of the computational approach. And the integrated multi-scale model can both describe the macroscopic mechanical behavior and mesoscopic heterogeneous damage evolution well. The integrated macroscopic and mesoscopic simulations are done concurrently in a coupled manner. Finally, two numerical examples are solved to demonstrate the accuracy and effectiveness of the approach.

2. Strategy for integrated multi-scale modeling of damage evolution with adaptive image-based method

Concrete is considered as a homogeneous material at the macro-scale, while it is usually considered as a three-phase material that consists of aggregates with a surrounding weak zone called ITZ embedded in matrix material when going down one scale, the so-called meso-scale [9]. It has been generally accepted that the fracture of brittle media, has two characteristics, i.e. catastrophe and sample-specificity due to its heterogeneous meso-components [4]. And the heterogeneous meso-level structure (namely aggregates, matrix material and ITZ) plays an important role in the failure process of concrete. Therefore, it is necessary to study the fracture mechanisms of concrete structures from the meso-scale point of view by incorporating the randomness of meso-component properties. And for modeling of the real random material meso-structural morphology accurately, the image-based numerical model is first needed [6]. However, as described above in the introduction, pure meso-scale simulations are generally limited to small specimens due to large demand of numerical effort and memory capability [7]. So, for large scale structures, the multi-scale modeling is necessary to study their fracture mechanism from meso-scale [13].

In the developed multi-scale computational approach, the macroscopic computations are executed in the regions of low gradients using homogenization-based continuum damage models where concrete is considered as macro-homogeneous quasi-brittle material, and the mesoscopic computations are executed in the regions of high gradients due to damage, where homogenization breaks down. As shown in Fig. 1, the whole computational domain Ω^{w} can be decomposed into a set of sub-domains (Ω^{macro}, Ω^{meso} and Ω^{trans}) without user intervention due to evolving damage. And all sub-domains are coupled and solved simultaneously. In order to facilitate the approach design and analysis, the sub-domains are divided into a set of representative volume elements (RVEs). The continuity of displacements and tractions at the interface between all sub-domains can be enforced using the Lagrange multipliers [6]. The details will be introduced in Section 4. And the sub-domains can be defined as follows:

Ω^{macro}: In sub-domain Ω^{macro} of low gradients, concrete is in elastic stage before the damage initiation and pure macroscopic analysis is executed ignoring its heterogeneous meso-components. Concrete is considered as homogeneous quasi-brittle material for the sub-domain, which is described using macro-RVE combining linear elastic theory, as shown in Fig. 1a.

Ω^{meso}: In sub-domain Ω^{meso} of high gradients due to damage, where homogenization breaks down, concrete is in damage stage and pure mesoscopic analysis is executed incorporating its heterogeneous meso-components. Concrete is considered as heterogeneous material for the sub-domain, which is described using meso-RVE based on the image of the realistic random meso-components combining damage model with different parameters of meso-components (meso-model parameters), as shown in Fig. 1b.

Ω^{trans}: Ω^{trans} is sandwiched between Ω^{macro} and Ω^{meso} for regularizing the incompatibilities at the interface between the two sub-domains, which is similar to the transition interface layer in Ref. [6]. Concrete is considered as homogeneous material for the sub-domain, which is described using trans-RVE combining damage model with model parameters of concrete as macro-homogeneous quasi-brittle material (macro-model parameters), as shown in Fig. 1c. Meanwhile, compared to Ω^{macro} and Ω^{meso}, Ω^{trans} is very small. So the loss accuracy due to describing the concrete damage evolution ignoring its meso-components in Ω^{trans} can be neglected.

In order to ensure the continuous changes in the computational model from macro- to meso-scale as a consequence of evolving damage in a reasonable way, adaptive scale change criterion is necessary. The developed adaptive scale change criterion coupled in the integrated multi-scale modeling can be described as follows:

As shown in Fig. 2, the initial FE model consists of only Ω^{macro}, where concrete is in elastic stage. Once the damage initiate in local area of Ω^{macro}, where homogenization breaks down, the heterogeneous meso-model can be adaptively implemented into the corresponding computational domain. In order to form a regular programmed pattern, the whole Ω^{macro} are discretized into many RVEs. The RVE in Ω^{macro}(macro-RVE) can be statistically representative of the material meso-components. And the damage threshold of every macro-RVE is monitored. Once the macro-RVE reaches the damage threshold, a RVE of meso-structure (meso-RVE) and a matching RVE of transition interface layer (trans-RVE) are implemented into the computational domain in the position of the macro-RVE. So in the multi-scale analysis, only the linear elasticity stage can be described in Ω^{macro}. Meanwhile, the area of macro-RVE S_{macro} is equal to the sum of area of meso-RVE S_{meso} and trans-RVE S_{trans}.

$$S_{macro} = S_{meso} + S_{trans} \tag{1}$$