Journal of Computational Science 12 (2016) 38–50

Contents lists available at ScienceDirect

Journal of Computational Science

journal homepage: www.elsevier.com/locate/jocs

Multi-scale modeling and trans-level simulation from material meso-damage to structural failure of reinforced concrete frame structures under seismic loading

Sun Bin [a,b], Zhaoxia Li [a,*]

[a] Department of Engineering Mechanics, Jiangsu Key Laboratory of Engineering Mechanics, Southeast University, Nanjing 210096, China
[b] Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 12 October 2015
Accepted 11 November 2015
Available online 2 December 2015

Keywords:
Adaptive
Concurrent multi-scale
Seismic
Damage
RC frame

ABSTRACT

An adaptive concurrent multi-scale method with three-level model is developed to simulate the trans-scale damage process of large concrete structures from meso-damage in material level to local damage and failure in component level and eventually to global deterioration in structural level. Adaptivity ensures level-change due to evolving damage for better effective without user intervention in the computation. To verify the effectiveness of the method, the trans-scale process of a RC (reinforced concrete) frame structure under seismic loading from meso-damage up to structural failure is simulated and compared with experiment. The results show that, the developed method can be used to reveal the seismic mechanisms of concrete structures by considering the trans-level coupling process from meso-damage to local failure in vulnerable component and eventually to structural failure in a concurrent way; and it is reliable in simulation on the seismic performance of large scale concrete-based structures with the adaptive capability as well as better computational efficiency for seismic risk mitigation plans.

1. Introduction

Monitor and study seismic damage evolution of the buildings to evaluate their performance suffering earthquake is still an important issue nowadays. Sritharan studied the seismic behavior of concrete bridge joint using the nonlinear finite element analyses [1]. Cofer evaluated seismic performance of RC (reinforced concrete) components [2]. Li carried out experimental and analytical investigations on the lightly reinforced concrete beam–column joints to study their seismic behavior [3]. Cesare studied global seismic damage behavior of RC buildings [4]. Gebreyohaness evaluated the seismic performance of RC wall buildings using the nonlinear dynamic procedure [5]. Predicting damage of structures suffering future earthquakes can be a very useful tool to evaluate the seismic performance for seismic risk mitigation plans [6,7]. In some works, concrete damage is interpreted using the tool of fracture mechanics [8–10]. And another useful way to predict damage is to develop damage model for calculating a damage index which normally has a value from zero to one. The value is close to zero when the structure remains elastic and close to one when the structure is global failure. Damage models may be broadly classified into two classes [11]: the first class is made up based on the mechanistic parameters like dissipated energy, deformation or sectional ductility of structural members [12–14]; the second class is made up based on the concept of continuum damage mechanics (CDM) [15–17]. Banon developed analytical models to predict seismic damage in RC frames based on the damage state parameters of flexural damage ratio and dissipated energy [12]. Park established a model to evaluate the structural damage based on the maximum deformation [13]. Heo evaluated the seismic performance of RC frame structures using probabilistic damage-based method by considering the stress–strain response of structural members [14]. Lee developed a new plastic-damage constitutive model for seismic analysis of concrete structures [15,16]. Suaris developed a damage model for describing monotonic and cyclic behavior of concrete [17]. Omidi described the seismic cracking response of concrete gravity dams using plastic–damage model [18]. And the damage of concrete beams due to shear action has been investigated [19–21].

In the recent researches on numerical studying of the seismic damage of concrete buildings, and concrete always is considered to be homogeneous material under the limitation of computation power and complexity of computation. However, failure of concrete

* Corresponding author. Tel.: +86 25 83790268; fax: +86 25 83792247.
E-mail addresses: binsun@seu.edu.cn (S. Bin), zhxli@seu.edu.cn (Z. Li).

http://dx.doi.org/10.1016/j.jocs.2015.11.003
1877-7503/

structures is a multi-scale coupling process from material level to component level and eventually to structural level [22]. And concrete is considered to be a highly heterogeneous material consisting of random constituents such as aggregates, matrix material and interfacial transition zone (ITZ) in meso-scale, which play a key role in the structural behavior [22]. Meanwhile, the real random heterogeneous meso-constituents have a strong influence on the stress distribution within concrete and, therefore, on the initiation, growth and coalescence of micro-cracks to the formation of macro-cracks, eventually to structural failure [23]. Therefore, in order to better understand the seismic failure mechanisms of concrete structures for evaluating their seismic performance, it is necessary to describe the trans-scale damage and failure process by considering the real random heterogeneous meso-constituents. However pure meso-scale analysis is limited to small specimen due to large memory demand. And the present methods such as developed by Ghosh [24,25], Oden [26], Lee [27,28], Belytschko [29], Greco et al. [30–32] and Nguyen [33], which also include the previous works of our team [34,35], can only focus on the two levels from material heterogeneity to homogeneity in component level. They are difficult to be used to describe the trans-level damage evolution of large scale structures starting from meso-scale.

Hence, this paper aims to develop an adaptive concurrent multi-scale FEM with three-level simulation of the trans-scale process from meso-damage up to structural failure of large concrete structures with sufficient precision and lower cost. As a case study of the method, the trans-scale damage and failure process of a large RC frame structure under seismic loading is simulated and compared with experimental results for verifying its effectiveness.

2. Strategy for the adaptive concurrent multi-scale method with three-level simulation

The problem of “how things break” still remains a compelling challenge until now due to its complexity [36]. In fact, the failure of structure is a multi-scale and trans-level phenomena from micro/meso- to macro-scale and across material, component and structural level, along with scaling and size effect. In order to better studying the damage and failure mechanisms of concrete structures stating from material heterogeneous in meso-scale with lower cost, a new adaptive concurrent multi-scale method is developed to simulate the trans-scale process from meso-damage up to structural failure, in which incorporates three-level model, respectively, describing non-key region, key region and damaged region with different sizes of elements and theory descriptions for better efficiency. The “concurrent” requires that all levels model be coupled for simultaneous solving. And the continuity of displacements and tractions at the interface between three-level models can be enforced using the Lagrange multipliers, which is the same way in Ref. [25]. And the description of the trans-scale damage and failure process in the developed method can be expressed as follows.

2.1. Level-1 $\left(\Omega^{meso}\right)$: Heterogeneous material level where damage evolving from meso- to macro-scale

Continuum damage model has been extensively applied to model the progressive degradation of material due to micro-cracking using a damage variable based on the concept of CDM [37]. And it is shown that in this way, the Mazars model can accurately model the behavior of concrete such as strain-softening response [38], in which the concrete is considered to be a homogeneous material. And the Mazars model can also be used to describe the deterioration behavior of concrete’s meso-constituents such as matrix, aggregate and ITZ due to its simplicity and good accuracy [23]. Therefore the Mazars model is chosen here for describing the damage evolution of concrete as macro-homogeneous material and its meso-constituents, respectively, with different macro- and meso-model parameters, which can be written as [38]:

$$D^{(*)} = \alpha_t^{(*)} D_t^{(*)} + \alpha_c^{(*)} D_c^{(*)} \times \left(* = \left\{\text{concrete}, \quad \text{aggregate}, \quad \text{matrix}, \quad \text{ITZ}\right\}\right) \tag{1}$$

where the weighting coefficients $\alpha_t^{(*)}$ and $\alpha_c^{(*)}$ are, respectively, written as:

$$\alpha_t^{(*)} = \frac{\sum_{i=1}^{3} H_i^{(*)} \varepsilon_{ti}^{(*)} \left(\varepsilon_{ti}^{(*)} + \varepsilon_{ci}^{(*)}\right)}{\varepsilon^{(*)2}} \tag{2}$$

$$\alpha_c^{(*)} = \frac{\sum_{i=1}^{3} H_i^{(*)} \varepsilon_{ci}^{(*)} \left(\varepsilon_{ti}^{(*)} + \varepsilon_{ci}^{(*)}\right)}{\varepsilon^{(*)2}} \tag{3}$$

$$H_i^{(*)} = \begin{cases} 0 & \left(\varepsilon_{ti}^{(*)} + \varepsilon_{ci}^{(*)} \le 0\right) \\ 1 & \left(\varepsilon_{ti}^{(*)} + \varepsilon_{ci}^{(*)} > 0\right) \end{cases} \tag{4}$$

where strains $\varepsilon_{ti}^{(*)}$ and $\varepsilon_{ci}^{(*)}$ due to positive $\sigma_+^{(*)}$ and negative stresses $\sigma_-^{(*)}$ can be written as:

$$\varepsilon_t^{(*)} = \left[\left(I - B^{(*)}\right) E^{(*)}\right]^{-1} \sigma_+^{(*)} \tag{5}$$

$$\varepsilon_c^{(*)} = \left[\left(\mathbf{I} - \mathbf{D}^{(*)}\right) \mathbf{E}^{(*)}\right]^{-1} \sigma_-^{(*)} \tag{6}$$

We call $\boldsymbol{\sigma}_+^{(*)}$ and $\boldsymbol{\sigma}_-^{(*)}$ the tensors in which, respectively, appear only the positive and negative principal stress, and $\boldsymbol{\varepsilon}_t^{(*)}$, $\boldsymbol{\varepsilon}_c^{(*)}$ the strain tensors. $D_t^{(*)}$ and $D_c^{(*)}$ can be written as:

$$D_t^{(*)} = \begin{cases} 0 & \varepsilon^{(*)} \le \varepsilon_{pt}^{(*)} \\ 1 - \dfrac{\varepsilon_{pt}^{(*)}\left(1 - A_t^{(*)}\right)}{\varepsilon^{(*)}} - \dfrac{A_t^{(*)}}{\exp\left[B_t^{(*)}\left(\varepsilon^{(*)} - \varepsilon_{pt}^{(*)}\right)\right]} & \varepsilon^{(*)} > \varepsilon_{pt}^{(*)} \end{cases} \quad \left(* = \left\{\text{concrete}, \quad \text{aggregate}, \quad \text{matrix}, \quad \text{ITZ}\right\}\right) \tag{7}$$

where $\varepsilon_{pt}^{(*)}$ is the strain threshold of tension damage, $A_t^{(*)}$, $B_t^{(*)}$ are model parameters of tension damage.

$$D_c^{(*)} = \begin{cases} 0 & \varepsilon^{(*)} \le \varepsilon_{pc}^{(*)} \\ 1 - \dfrac{\varepsilon_{pc}^{(*)}\left(1 - A_c^{(*)}\right)}{\varepsilon^{(*)}} - \dfrac{A_c^{(*)}}{\exp\left[B_c^{(*)}\left(\varepsilon^{(*)} - \varepsilon_{pc}^{(*)}\right)\right]} & \varepsilon^{(*)} > \varepsilon_{pc}^{(*)} \end{cases} \quad \left(* = \left\{\text{concrete}, \quad \text{aggregate}, \quad \text{matrix}, \quad \text{ITZ}\right\}\right) \tag{8}$$

where $\varepsilon_{pc}^{(*)}$ is the strain threshold of compression damage, $A_c^{(*)}$, $B_c^{(*)}$ are model parameters for compression damage.