Construction and Building Materials 80 (2015) 262–272

Contents lists available at ScienceDirect

Construction and Building Materials

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

Monte Carlo simulations of mesoscale fracture of concrete with random aggregates and pores: a size effect study

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HIGHLIGHTS

- Size effect of concrete studied by realistic mesoscale models and Monte Carlo simulations.
- Key meso-control parameters (aggregate fraction and porosity) considered.
- Weibull size effect laws of strength obtained considering the key parameters.
- Equations relating strength and the key parameters obtained.
- Both aggregate fraction and porosity play significant role.

ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form 22 January 2015
Accepted 3 February 2015

Keywords:
Concrete
Size effect
Monte Carlo simulations
Cohesive crack models
Meso-scale modelling

ABSTRACT

Size effect in concrete under tension is studied by Monte Carlo simulations of mesoscale finite element models containing random inclusions (aggregates and pores) with prescribed volume fractions, shapes and size distributions (called meso-structure controls). For a given size and a set of controls, a number of realisations with different spatial distribution of inclusions are simulated to produce statistical data for macroscopic load/stress–strain curves. The complex meso-crack initiation and propagation is captured by pre-inserted cohesive interface elements. The effects of specimen size and meso-structure controls on macroscopic strength and toughness are analysed, and empirical size-effect laws for their dependences are proposed by data regression. It is also shown that the mesoscale porosity affects both strength and toughness and should not be ignored in size effect studies of concrete.

1. Introduction

Concrete is a composite material with random arrangements of mesoscale (mm) constituents of different mechanical properties. The effect of the resultant heterogeneous meso-structure on the mechanical behaviour is strong when the specimen size is comparable to the sizes of characteristic constituents, making homogenisation questionable. The effect weakens and the homogenisation becomes increasingly valid as the specimen size increases. This is a "structure–property" explanation of the measurable changes in mechanical behaviour with specimen size, known as the size effect [1,2]. The size effect of concrete has been widely investigated experimentally and numerically since 1990s [1,3–10]. It has been shown that the nominal strength of concrete can decrease significantly with increasing specimen size, which is now regarded as an inherent concrete behaviour [11–13].

Different theories have been developed to explain the size effect, amongst which the best known are the works of Weibull [14], Bazant [15] and Carpinteri [16]. It appears that the size effect needs to be investigated by a bottom-up approach, with explicit account of concrete non-homogeneous structure, replicated in specimens of increasing sizes. This is an experimentally challenging task, but can be tackled by increasingly realistic numerical models. For example, Van Mier et al. [1,17] and Grassl et al. [18,19] used discrete lattice model to study the size effect of quasi-brittle materials. Karihaloo et al. [20] and Duan et al. [6] used the fictitious crack model to investigate the size effect on concrete. However, mesoscale numerical studies of the size effect of concrete with statistical analyses are still challenging [21–23], mainly due to the complex multi-phase composition, the complicated nonlinear multi-cracking behaviour, and substantial computational cost from repetitive simulations.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.02.002
0950-0618/

In this paper, we study the size effect in concrete under tension by Monte Carlo simulations (MCS) of mesoscale specimens of varying sizes. The direct parameterisation modelling technique [24–26] is used to build mesoscale concrete models with randomly-distributed aggregates and pores generated according to prescribed size distributions, shapes and volume fractions. The four different phases, i.e., mortar, aggregates, interfaces and pores are explicitly modelled, allowing for examination of their relative influences on meso/macro mechanical responses. The complicate meso-crack initiation, propagation and coalesce into macro-cracks is captured by pre-inserted cohesive interface elements into solid finite element (FE) meshes [23,27]. The detailed procedure and initial results have been presented in [23].

The size effect of concrete nominal strength is mostly analysed by pre-notched beams under three-point bending [20,28–30]. However, such loading conditions complicate the analysis and understanding of the size effect on the failure processes due to the strain and stress gradients introduced. Therefore, this study is focused on analyses of specimens without notches under displacement-controlled uniaxial tension. Such analyses replicate standard tensile tests, where stress concentrator is not present initially. This allows us to study a spatially distributed micro-cracking prior to localisation into a macroscopic crack, rather than to predefine localisation with the presence of a concentrator. The size effect caused by stochasticity, namely more defects are included as the size increases, and the deterministic size effect caused by nonlinear fracture process, were both taken into account. The macroscopic properties of interest in this study are strength and toughness. These are calculated by statistical analyses of a number of realisations. The effects of specimen size and the main meso-structure controls (volume fractions and size distributions of aggregates and pores) on these properties are analysed and empirical expressions for their dependences are proposed.

The outline of the paper is as follows. In Section 2 we present the techniques for generation of inhomogeneous meso-structures and the basics of finite element modelling with cohesive interfacial elements. In Section 3 we report and discuss the results of size effects in concrete with different prescribed parameters and propose several size effect laws based on them. The main conclusions are drawn in Section 4.

2. Model and method

The detailed procedure of generating numerical concrete samples and inserting cohesive interface elements into solid FE meshes has been given in [23] and [27]. Herein only an outline is presented for the convenience of discussion.

2.1. Generation of numerical concrete samples

The size distribution of aggregates in concrete is often described by the Fuller curve [31], which is discretised into a number of segments. The aggregate size distribution reported by Hirsch [32] and summarised in Table 1 is used in this study. The concrete contains coarse and fine aggregates and the cut-off size between coarse and fine aggregates is taken to be 2.36 mm. Here only coarse aggregates are explicitly modelled as meso-scale features. The large number of fine aggregates together with the cement matrix is regarded as mortar with homogenised uniform mechanical properties. The coarse aggregates are considered to have elliptical shape. In most concretes, the volume density of coarse aggregates is between 40% and 50% [33]. Elliptical pores are introduced with uniformly distributed sizes in the range from 2 to 4 mm. The prescribed volume fractions of aggregates and pores (i.e., porosity) are met by generating spatially-distributed random aggregates and pores in a repeated manner until a target area is filled [23].

Table 1
Aggregate size distribution [32].

Sieve size (mm)	Total percentage retained (%)	Total percentage passing (%)
12.70	0	100
9.50	39	61
4.75	90	10
2.36	98.6	1.4

2D square numerical samples are generated. Fig. 1 shows five typical models with different sizes or length L and Fig. 2 shows five samples with $L = 50$ mm, using the following parameters: aggregate volume fraction $P_{agg} = 40\%$, porosity $P_{pore} = 2\%$, aspect ratio for elliptical aggregates and pores $R_1 = R_2 = [2, 2.5]$, minimum space between the edge of an aggregate and the specimen boundary $\gamma_1 = 0.5$ mm and minimum gap between any two aggregates/pores $\gamma_2 = 0.5$ mm.

2.2. Finite element mesh generation and fracture modelling

The numerical concrete models are then meshed in ANSYS automatically by running a batch file of APDL programs, so that a large number of samples can be meshed quickly for Monte Carlo simulations and statistical analyses. The 4-noded cohesive interface elements (CIEs) with zero in-plane thickness are then inserted into the generated solid FE mesh (triangular plane stress elements) by an augmented procedure devised for homogeneous materials in [27] to account for multi-phases and interfaces. CIEs with different traction–separation softening laws are inserted inside the aggregates, inside the mortar, and on the aggregate-mortar interfaces, respectively, to simulate the complicated nonlinear fracture behaviour [23,34].

The cohesive element COH2D4 with zero in-plane thickness in ABAQUS is used in this model. Its constitutive behaviour is described by a damage initiation criterion and a damage evolution law. A bilinear cohesive zone model, illustrated in Fig. 3, was used in this work.

The damage is assumed to initiate when the following condition is met:

$$\left\{\frac{\langle t_n\rangle}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 = 1 \tag{1}$$

where $\langle\ \rangle$ is the Macaulay bracket, i.e.,

$$\langle\delta_n\rangle = \begin{cases} \delta_n, & \delta_n \geqslant 0 \text{ (tension)} \\ 0, & \delta_n < 0 \text{ (compression)} \end{cases} \tag{2}$$

The damage evolution is characterised by a scalar parameter, D, representing the overall extension of the crack across the element caused by all physical mechanisms. It is defined in terms of effective relative displacement δ_m given by:

$$\delta_m = \sqrt{\langle\delta_n\rangle^2 + \delta_s^2} \tag{3}$$

The definition of the damage parameter D is:

$$D = \frac{\delta_{mf}\ (\delta_{m,\max} - \delta_{m0})}{\delta_{m,\max}\ (\delta_{mf} - \delta_{m0})} \tag{4}$$

where $\delta_{m,\max}$ is the maximum effective relative displacement attained during the loading history, and δ_{m0} and δ_{mf} are effective relative displacements corresponding to δ_{n0} and $\delta_{s0,}$ and δ_{nf} and δ_{sf} in Fig. 3, respectively. D evolves monotonically from 0 to 1 upon further loading after the initiation of damage.

The damage initiation and evolution degrades the unloading and reloading stiffness coefficients, k_n and k_s, calculated by: