Computers and Structures 173 (2016) 1–18

Contents lists available at ScienceDirect

Computers and Structures

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

A concrete homogenisation technique at meso-scale level accounting for damaging behaviour of cement paste and aggregates

Loredana Contrafatto, Massimo Cuomo *, Salvatore Gazzo

Department of Civil Engineering and Architecture, Division of Structural Engineering, University of Catania, Italy

ARTICLE INFO

Article history:
Received 7 October 2015
Accepted 5 May 2016
Available online 7 June 2016

Keywords:
Concrete
Meso-scale
Random generation
Homogenisation
Damage

ABSTRACT

Concrete is an heterogeneous structural material whose constitutive behaviour is strictly depending on the mechanical properties of the aggregates and the cement paste. A large number of methods have been devoted to the prediction of the mechanical properties of this material by means of meso-scale analysis. The paper concerns a new meso-scale model of concrete, that considers the composite as a multi-phase material. The numerical description of the meso-scale structure is attained using a random method that allocates at each Gauss point of the finite element discretisation of the Representative Volume Element (RVE) a specific phase of the mixture: aggregate, cement paste, void. Each phase is characterised by a specific non linear constitutive model, whose parameters have been determined by means of experimental tests on the components. More experimental tests have been performed on concrete samples, and they have been numerically reproduced by means of the proposed procedure. Numerical simulations of cyclic uniaxial compression tests have shown the ability of the meso-model to correctly predict the peak strength, the tangent and secant elastic stiffness of the mixture for strains above the peak strain, even adopting a relatively coarse finite element discretisation of the RVE.

1. Introduction

Mechanical as well as physical properties of concrete strongly depend on the composition of the material, that is, the type of cement, the mechanical and geometrical properties of the aggregates, the presence of additives. A proper mix design is needed in order to get the required mechanical properties, and the required durability. Indeed it is well known that a wrong mix of the distribution of the aggregates can dramatically hinder the development of the required strength, even in the presence of high strength cement. The evaluation of the performance of the mixture starting from the properties of the constituents is of great engineering relevance, so that the material can be adequately designed. The mix design of concrete is usually performed on the basis of empirical correlations, and a substantial amount of experimentation is required in order to get the desired results. Once the concrete has been designed, the numerical simulation of structural elements is performed at a macroscopic level assigning homogenised mechanical properties. A failure criterion is selected, in the field of Plasticity, possibly with softening, or in the field of Continuum Damage Mechanics, possibly coupled with plastic irreversible strains. These approaches require the identification of many material parameters, specific to each type of concrete.

A meso-scale model of concrete, that considers the concrete as a multi-phase material, can thus be of interest either in aiding the design of the material, especially when special properties are required, and in the mechanical analysis at the structural level, by means of multi-scale methods, that can be more accurate in predicting the complex non linear response of concrete. In [1] the importance of numerical analysis for the prediction of the mechanical behaviour of concrete mixture is highlighted, based on the consideration that a really wide variety of possible concrete types exists or can be conceived, combining a multitude of aggregate types (river gravel, quarry crushed gravel, recycled material, different kinds of fibers and microfibers) with different matrix materials (cementitious paste of different nature), and various additives (accelerating admixtures, retarding admixtures, fly ash, air entraining admixtures, water-reducing admixtures).

A large number of scientific researches has been devoted to the numerical prediction of the mechanical properties of composite cementitious materials by means of meso-scale analysis [1–11]. Each component of the heterogeneous composite is individually modelled and, after assigning appropriate constitutive and kinematic models, the response of the composite can be simulated, including the evolution of the damaging process. The local consti-

* Corresponding author.
E-mail addresses: loredana.contrafatto@dica.unict.it (L. Contrafatto), massimo.cuomo@dica.unict.it (M. Cuomo), salvatore.gazzo@studium.unict.it (S. Gazzo).

http://dx.doi.org/10.1016/j.compstruc.2016.05.009
0045-7949/

tutive response can then be obtained at the macro level applying homogenisation techniques. A Representative Volume Element (RVE) [12] has to be defined, whose dimension depends on the maximum size of the constituents of the heterogeneous material and must be such that the identified mechanical properties are statistically representative of the composite. The existence of a RVE for a highly random material like concrete is a matter of discussion, so that we emphasize that it has to be defined at a statistical level, and that a dispersion in the results of the numerical predictions based on the RVE must be expected. In the linear range this approximation must fulfil the upper and lower bounds given by Voigt and Reuss [13–15]. It has also been observed that in the case of concrete, especially if the softening behaviour is investigated, a method accounting for strong coupling between the meso and macro scales should be used, like those proposed in [16–18]. The present work, however, is limited to the analysis of the meso-level model.

It is important to point out that the use of mixture theory is not appropriate for the problem at hand, as can be observed analysing the properties of cement paste, aggregates and concrete reported in Section 4.3. Nonlinearities due to the development of damage in the phases play a very important role, so that a non linear meso-scale analysis is required. Also it has to be stressed the importance of voids, that can be viewed as a soft phase. Voids can be generated either for the effect of geometrical packaging of the aggregates, in the case of mixtures poor in cement content, or for the effect of hydration in the cement paste. In this work only the second case is considered.

In [19] a computational homogenisation procedure for samples with irregular microstructure has been developed. The linear displacement boundary conditions and the uniform traction boundary conditions, satisfying Hills energy criterion, were used for estimating the effective material properties. In principle, periodic boundary conditions should be applied to the RVE, according to the mathematical theory of homogenisation. As observed in [20], the presence of soft phases or voids in the vicinity of the boundary can generate excessively deformed meshes such that the evaluation of the stress distribution in the sample becomes ill conditioned. The window method, applied in [5,20] is a possible strategy to overcome this undesirable effect and to obtain optimal convergence behaviour of the homogenisation results, regardless of the type of the imposed boundary conditions.

The main problem in the meso-scale analysis of randomly distributed media concerns the generation of the microstructure. Some of the methods proposed and commonly used are examined in Section 2. They are based on a simplification of the concrete microstructure, that is reduced to a limited number of distinct components, generally the cement paste, the aggregates and sometimes an interface transition zone (ITZ). Then the components are arranged in the RVE trying to approximate the particle distribution, and a meshing procedure is employed. Aligned or unaligned approaches have been proposed. In the first case the boundaries of the discretised components coincide with material interfaces and no material discontinuity is present inside the finite elements [21–26]. In the second case, the unaligned mesh leads to material discontinuities inside the finite elements [27,9]. An Interface Transition Zone (ITZ) can also be introduced, for simulating the failure modes at the interface between the main phases [28,22,29]. In the latter category fall also the models of grains interacting through non linear beams like [30,31]. In both cases if the nonlinear properties of the material are associated with the interfaces, special attention has to be given to the continuity of the inter-element stresses, and this requires either special recovery procedure for the stresses, like in [32,33] or interpolations with high continuity degree, like in [34,35].

In the paper we propose a new method for the numerical simulation of cementitious material in the framework of meso-scale analysis. The distribution of the concrete components in the RVE is obtained using a random method that allocates at each Gauss point of the mesh of the RVE a specific phase of the mixture: aggregate, cement paste, void. Specifically, the constitutive model of the phase is assigned at the Gauss point depending on a random function of the volume fractions of the mixture components, that respects the grading curve. Therefore, the model does not consider the physical size of the components. The approach is different from most previous proposals that discretise the RVE following the geometry of the aggregates and in this way it allows to overcome the difficulties met with aligned or non aligned meshes. The evolutive behaviour of the cement paste and of the aggregate is ruled by an elastic–plastic constitutive model coupled with damage [36].

It is well known that for materials with microstructure meso-scale analysis requires to solve a sequence of problems characterised by higher order deformation measures [37–45]. It is interesting to underline that when higher gradient deformation measures are introduced, additional edge boundary conditions arise, that enrich the kinematical description of the RVE [46–51]. Details about the connection of second gradient deformation theory with the deformation modes of structural models can be found in [52–54], while for a collection of recent results, see [55]. Following this path of reasoning the homogenisation model could possibly be enhanced in order to account for phenomena, like those related to transition zones, that in this work are disregarded. However, in this paper only a first order homogenisation procedure is applied, since the emphasis is particularly focused on non linear simulations at the constitutive level.

The analyses performed in this paper relate to the meso-scale only, and are aimed to simulate the constitutive behaviour of the material, in order to evaluate the reliability and the limits of the method proposed, as done in [25,3,56,9]. The method will be presented and only the results of uniaxial compression processes will be reported in this work. As it will be shown comparing the results of the simulations with original experimental results, the method allows, for the case examined, to correctly predict the elastic properties of the mixture, as well as the peak strength and the damage development. The results are independent from the random process used for generating the meso-scale and from the mesh size, provided an adequate number of elements is used in the discretisation.

The organisation of the paper is as follows: in Section 2 the proposed procedure for the generation of concrete meso-structure is presented. Section 3 illustrates the constitutive model of the phases that constitute the composite. Section 4 and its subsections report the experimental programme carried out to obtain the main constitutive parameters of the phases needed to numerically characterise the concrete, as described in Section 3. Section 5 concerns numerical simulations of the behaviour of the phases and of concrete. In Section 5.2 the calibration of the constitutive model for each phase is presented, by fitting the experimental curves. Successively, in Section 5.3 different types of generation of the concrete meso-scale are presented and numerical tests are compared with the experiments described in Section 4.3.3.

2. Generation of concrete meso-structure

Concrete is regarded at the meso-scale as a composite material with a finite number of deterministically distinct phases, which correspond to its main components. The distribution of the phases has to comply with the mix design used for the composition of the material. A Representative Volume Element (RVE) is defined, whose dimension is correlated to the maximum aggregate size.