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Modeling of the quasibrittle fracture of concrete at meso-scale: Effect of classes of aggregates on global and local behavior

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ABSTRACT

The computational power allows nowadays the development of mesoscopic models of concrete, based on finite element or lattices approaches, which represent the contribution of inclusions to the behavior of concrete. However, the smallest heterogeneities are often removed to these simulations for decreasing the computation time. In this paper, the effect of aggregate classes on the fracture behavior of a plain concrete is studied. Different simulations are performed from a mesoscopic model based on a diffuse meshing technique and Fichant's damage model, in which the smallest aggregates are successively removed from the granular skeleton to the benefit of a homogenized continuous mortar. The effects of these simplifications are then evaluated by comparing the fracture behaviors obtained to the one of the reference concrete. The results show the relevance of modeling all classes of aggregates in order to obtain an accurate description of the failure behavior of concrete.

1. Introduction

The accurate description of concrete behavior through a macroscopic constitutive law is complicated by the high heterogeneities of cementitious materials. During the fracture process, after elastic and homogeneous strains, a micro-cracked zone called the Fracture Process Zone (FPZ) appears before the peak load. This damaged zone, formed by matrix microcracking, debonding of cement-aggregate interface, and grain bridging, tends to develop and to localize into a macro-crack, and finally critically propagates during the loading. This nonlinear zone is responsible for the dissipation of the elastic energy stored in the structure due to stress transfer. Commonly such behavior is called quasi-brittle. The characterization of the FPZ (by numerical [1] or experimental [2] analysis) constitutes a major challenge for the understanding of concrete mechanical behavior. Concerning the global mechanical response, a softening behavior occurs due to strain/damage localization (LEFM cannot correctly represent the stress field), and this has to be explicitly taken into account [3]. Concrete is a composite material with significant heterogeneities which have an important influence on concrete behavior at failure. The structure of concrete can be considered as a multi-level hierarchy system (macro-meso-micro-nanolevel) [4]. In this case, interaction between various components of concrete is required in order to accurately simulate the softening behavior, the damage fields and the crack paths, and to investigate the influence of concrete composition on the macroscopic properties [5]. Currently the computational power of computers allows the development of many non-linear models at mesoscale which present a real interest for describing the complex failure of concrete, ranging from diffuse failure to localization and final discrete failure. Nevertheless, most mesoscopic models are forced to simplify the concrete microstructure, representing only the largest aggregates because of the difficulty of meshing the smallest aggregates and the corresponding increase in computation time. The main question is what is the consequence of such simplification of concrete microstructure on the relevance of the simulated behavior. Indeed, mechanical and physical properties of concrete are dependent on the volume fraction and properties of the constituents [6]. The mesolevel approach is useful for analyzing the influence of aggregates on the failure behavior of concrete which is affected by the size, shape and grading of aggregates [7]. Moreover, during the failure process, the crack pattern (tortuosity) is governed by the position of the coarse aggregates. Generally aggregates are the cause of tougher, stiffer and more ductile behavior of concrete as the volume fraction of fine and coarse aggregates is increased without changing their grading [8]. The use of non-linear models at mesolevel can be performed by applying the

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Nomenclature

B_t	Parameter of the damage evolution law
C_{ijkl}	Elastic stiffness tensor components
D	internal variable for damage
E	elastic modulus
fg_i	volume fraction of aggregates per class i
f_t	tensile strength
Fvg	global volume fraction of aggregates
G_f	fracture energy
h	element size
I_1	First principal invariant of the effective stress
J_2	Second principal invariant of the deviatoric part of the effective stress
Ke_{ij}	elementary stiffness matrix
L_{REV}	length of the Representative Elementary Volume
$\varnothing_i$	aggregate diameter of the class i
$\varnothing_{max}$	maximum aggregate diameter i
$\varnothing_{min}$	minimum aggregate diameter i
W_F	Work of the fracture
X_i	first coordinate of an aggregate
Y_i	second coordinate of an aggregate

Greek symbols

ε^e_{kl}	Elastic Strain tensor components
ε_{eq}	Equivalent Strain
η_g	second coordinate of a Gauss point g
ξ_g	first coordinate of a Gauss point g
$\tilde{\sigma}_{ij}$	Effective Stress tensor components
σ_{ij}	Stress tensor components
ω_g	Weight associated with the Gauss point g

Abbreviations

BFGS	Broyden–Fletcher–Goldfarb–Shanno algorithm
FPZ	Fracture Process Zone
H	homogenized
HM	homogenized mortar
HPC	high performance concrete
ITZ	Interfacial Transition Zone
M	Missing
P	Present
REV	Representative Elementary Volume

Finite Element Method [9], the Discrete Element Method [10] or the resource-intensive lattice method [11]. Because of the difficulty of meshing together small and large aggregates, most authors merely model the largest aggregates. The matrix is then composed with a mortar that accounts for the smallest aggregates.

The aim of this paper is to present the influence of small aggregates on the failure behavior of plain concrete by the use of a damage constitutive law simulated from a Finite Element Model established at mesolevel, i.e., taking into consideration the roles of the cement matrix and of the aggregates. The damage model used for the simulation of the fracture behavior of concrete is an isotropic damage model developed by Fichant et al. [12], that takes into account the unilateral effects, used at the mesoscale of concrete for both aggregates and matrix. The model is implemented in the finite elements code Cast3M©. Moreover, a diffuse meshing method is used, whereby the matrix and aggregates properties are projected on the shape functions of the finite element mesh. For this study, the accurate representation of the aggregates compactness is priority, that is a reason why the Interfacial Transition Zone (ITZ) is not represented in this mesoscopic model. Moreover, its mechanical parameters are difficult to assess and the use of a diffuse meshing method may offset this issue. Thus, in this mesoscopic model, a “natural” ITZ takes place since elastic and fracture parameters contrasts lead to a stress concentration and, thus, damage localizes at the paste-aggregates interface. In the following the parameters used for cement paste and aggregates refer to normal concrete for which intragranular cracking is expected. Indeed, in a plain concrete the aggregates are not expected to damage. Thus, in this case, the aggregates can be seen as strong inclusions and lead to tortuous crack path and consequently to a crack-path dependent fracture energy. This concrete configuration seems to be more appropriate in order to study the effect of aggregates classes on the fracture behavior compared to the case of high performance concretes (HPC). The model is also able to capture trans-granular cracking by adopting appropriate parameters which is more appropriate for high performance concretes.

In this paper, the isotropic damage model [12] is presented along with the generation process of the mesostrucrure of concrete, as well as the estimation procedure of the mechanical and fracture properties of the aggregates and the mortar matrix. The computing strategy used to investigate the influence of aggregate classes on the fracture behavior is then explained. Finally, the relevance of modeling all or part of the aggregate classes of concrete by a numerical homogenization method is studied and discussed.

2. Constitutive damage model

2.1. Principle of the constitutive model

The damage model used is the isotropic damage model developed by Fichant [13], which is an extension of Mazars' model [14] taking into account the unilateral effect of concrete and inelastic strains (plasticity). The microcracking effect is directly linked to the internal state damage variable D. This damage variable is ranged from 0, for an undamaged material, to 1, for a fully damaged material. The notions of damaged and undamaged lead to the concept of effective stress $\tilde{\sigma}$(1), which represents the necessary stress to apply to an undamaged material element so that it deforms the same way as a damaged element under total stress σ (2).

$$\tilde{\sigma}_{ij} = C^0_{ijkl} : \varepsilon^e_{kl}, \tag{1}$$

where ε^e_{kl} is the local elastic strain fields and C^0_{ijkl} the initial isotropic elastic stiffness tensor. The total stress is described by:

$$\sigma_{ij} = C^{damaged}_{ijkl} : \varepsilon^e_{kl}, \tag{2}$$

where $C^{damaged}_{ijkl}$ is the damaged material stiffness tensor.

Based on Eqs. (1) and (2), the relation between total and effective stress can written as follows:

$$\sigma_{ij} = C^{damaged}_{ijkl} : \left(C^0_{klmn}\right)^{-1} : \tilde{\sigma}_{mn} = (1 - D)\tilde{\sigma}_{mn}, \tag{3}$$

where $(C^0_{klmn})^{-1}$ is the initial compliance tensor and D the scalar variable of the isotropic model. The evolution of the isotropic damage variable D is expressed as an exponential law:

$$D = 1 - \frac{\varepsilon_{d0}}{\varepsilon_{eq}} \exp(B_t(\varepsilon_{d0} - \varepsilon_{eq})), \tag{4}$$

where $B_t = \frac{hf_t}{G_f - 0.5 f_t \varepsilon_{d0} h}$ is a damage parameter driving the shape of the strain softening and in which f_t is the tensile strength, G_f is the fracture energy and h corresponds to the size of the finite element (in