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A mesoscale fracture model for concrete

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ABSTRACT

We analyze the dynamic failure of concrete using two and three-dimensional finite-element models. In particular, the current results extend, using a unique parallel computing approach, previously published two-dimensional results. Concrete is treated at the mesoscale with an explicit representation of coarse aggregates and mortar paste. The propagation and coalescence of cracks are modeled with dynamically inserted cohesive elements. Stress-strain response, dissipated fracture energy and crack evolution are compared under tensile loading at several strain rates. The artifacts of the two-dimensional approach regarding microcrack coalescence are discussed in detail. Nonetheless, the dynamic increase factors for the peak strength and dissipated fracture energy show that in both two and three dimensions, micro-inertial effects are not enough to simulate the rate dependency in concrete with a simple rate-independent cohesive law. Rate-dependent damage parameters can be introduced to obtain a more accurate dynamic response.

1. Introduction

Concrete, one of the most important construction materials, is broadly used in various industrial and civil structures. Earthquakes, explosions and collisions are typical examples of dynamic loading that a structure made of concrete can experience during its service time period. It is vital to investigate and understand thoroughly the dynamical mechanical response of concrete.

Concrete can be modeled at different length scales: macrolevel, mesolevel, microlevel [1] and nanolevel. At the macroscopic level (m), concrete is usually represented as a homogeneous material. First level heterogeneities are introduced at the mesoscale level, these are coarse aggregates, mortar paste and the interfacial transition zone. At the microscale, mortar matrix is modeled as a combination of fine aggregates and hardened cement paste. The nanolevel is now often proposed in addition to the classical scales of interest, as the novel approaches of nanotechnology can improve macroscopic properties such as strength and toughness [2,3].

Several efforts can be found in the literature to model concrete both at the macroscale and mesoscale [4–9]. Damage models often coupled with plasticity are widely employed at the macroscale with continuum elements. At the mesoscale two popular computational class of methods can be considered based on the representation of the computational domain. A first representation is realized by lattice models where the continuum is depicted by a collection of discrete elements called lattice beams. The heterogeneity of a concrete mesostructure is modeled by adjusting the mechanical properties of these beams while fracture is accounted with the beam stiffness deterioration and eventual removal [10–15]. The second class is the finite-element approach, in which concrete is represented as a two-phase material consisting of aggregates and mortar paste with an interfacial transition zone in between [16–23]. Both approaches seem to capture the overall characteristics of dynamical mechanical behavior of concrete such as crack propagation, coalescence and localization in the specimens. Hence, the representation of concrete at the mesoscale can be thought as a suitable level to investigate the fracture characteristics.

The efforts regarding the modeling and analysis of concrete are mostly limited to two dimensions because of the computational complexity and cost of the problem. There are several three-dimensional attempts using discrete-element models [13,24-28] and with finite elements [29–36] but with rather coarse mesh discretization. Parallel computing is essential to tackle concrete fracture at the mesoscale with necessarily fine discretization in three-dimensional space. Our open-source finite-element code Akantu gives the possibility to solve multi-million degrees of freedom with cohesive element capability [37]. With the help of this software, three-dimensional mesoscale modeling of concrete is within reach with an adequate level of detail.

The objective of this paper is to analyze the dynamic failure in concrete in terms of rate dependency of peak strength and dissipated energy. We aim to provide a physics-based understanding of microcracks evolution using a unique capability of three-dimensional modeling and extending the approach previously published in two dimensions [20,23]. In Section 2, we describe the generation of concrete

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mesostructures using a distribution of coarse aggregates thus finer aggregates are implicitly represented in the homogenized response of the mortar matrix to reduce computational cost. We build models for two and three dimensions with the same packing density and distribution constants to allow a rigorous comparison between them. In Section 3, the cohesive-element method is presented to model crack initiation and propagation in the concrete specimens. The mechanical problem and numerical setup are introduced in Section 4 along with details regarding the parallel implementation. Section 5 presents a sensitivity analysis to ensure that the obtained crack patterns are not affected by the choice of the time step. In Section 6, the differences between two and three-dimensional analysis results are compared in terms of the macroscopic stress response, energy dissipation characteristics and crack cluster statistics. The artifacts concerning crack propagation and coalescence of a two-dimensional representation are illustrated. While a three-dimensional model removes those artifacts, we aim to illustrate in Section 7, that a simple rate-independent cohesive law is not enough to capture experimentally-observed values of strain-rate strengthening. Both two and three dimensional mesoscale concrete models need to incorporate rate-dependent damage parameters.

2. Mesostructure generation

At the mesoscale, concrete is modeled by coarse aggregates, mortar paste and an interfacial transition zone. The shape and surface roughness of the aggregates depend on the aggregate type. Commonly, gravel aggregates have a smoother surface while crushed rock aggregates resemble sharp-edged angular particles [38]. In the literature, one can find various attempts for the generation of the geometry of aggregate particles from round to arbitrary shapes. In this study, coarse aggregates are geometrically modeled with circles and spheres in two and three-dimensional spaces respectively.

The particle size distribution of aggregates are obtained by means of a sieving method that uses the Fuller distribution curve, one of the most known and acceptable models to design numerical concrete. It is denoted by the following formula [39]:

$$P(d)=100\left(\frac{d}{d_{\max}}\right)^{n} \tag{1}$$

where $P(d)$ is the total percentage of aggregates that pass a sieve of diameter d, $d_{\max}$ is the maximum aggregate diameter and n is an exponent, which typically takes values between 0.45 and 0.7. Similarly to the work of Gatuingt et al. [23] and since only the coarse aggregates are modeled, a packing density of 30% is used to generate concrete mesostructures.[1] The diameter of the maximum aggregate for the specimens is 16 mm while the minimum is 4 mm. The aggregates are placed in the square (2-D) and cubic (3-D) specimens of side length 100 mm, which are representative volumes to accurately assess the macroscopic properties.[2]

We place the coarse aggregates into the specimen using a random placement technique addressed as take-and-place method [19]. The coarse aggregates are taken from a pre-specified grading curve and then placed in the specimen considering there should be no overlap between the aggregates that are already placed. In order to ensure the non-overlapping aggregates condition, a minimum distance for two aggregate particles A and B can be defined as follows:

$$d_{\min,AB}=\gamma\,(r_A+r_B) \tag{2}$$

where r_A and r_B are the radii of particles A and B and γ is a distribution factor. We use here a value of 0.1 as proposed by Schlanger and van Mier [10]. This minimum distance also ensures that the aggregates are coated with a mortar film having some thickness. Bigger distribution factors imply that the aggregates are distributed in the specimen more uniformly. Wittmann et al. [1] reported that the thickness of mortar film decreases as the aggregate density increases. In light of this, the trade-off in the selection of the distribution factor is apparent. Aggregates are packed more easily with the smaller distribution factors but their distribution is less homogeneous in the mesostructure. General practice is to try a sufficiently high factor for a given packing density to sustain an adequate level of homogeneity.

The mesoscale models generated following the defined procedure above in two and three dimensions are illustrated in Fig. 1. Identical packing densities and distribution factors are used in both models, respectively 30% and 0.1.

3. Cohesive element method

The cohesive element method is used to model dynamic fracture in concrete. The method is based on the cohesive crack model of Dugdale [41] and Barenblatt [42]. To represent the decohesion we bury all complex debonding processes in a phenomenological, simple, cohesive law relating the traction and opening displacement. This constitutive response is called traction-separation law:

$$\mathbf{T}=\mathbf{T}(\boldsymbol{\Delta}), \tag{3}$$

where $\mathbf{T}$ is the traction acting on the separating surfaces and Δ is the relative opening displacement vector. We use a simple linear irreversible softening law [43,44]. The existing free potential energy ϕ, is assumed to depend only on one effective scalar displacement δ of the following form:

$$\delta=\sqrt{\Delta_n^2+\beta^2\Delta_s^2}, \tag{4}$$

where Δ_n and Δ_s are the normal and tangential displacement components while β is the parameter that couples these two displacements. This parameter can be estimated by imposing lateral confinement on specimens subjected to high strain rate axial compression [45] and roughly defines the ratio of K_{IIc} to K_{Ic} of the material [46]. We choose $\beta = 1$ in line with the previously published two-dimensional studies [20,23]. The derivation of free potential energy with respect to the opening displacement gives the cohesive tractions:

$$\mathbf{T}=\frac{\partial\phi}{\partial\boldsymbol{\Delta}}=\frac{T}{\delta}(\Delta_n\mathbf{n}+\beta^2\Delta_s\mathbf{s}), \tag{5}$$

where $\mathbf{n}$ and $\mathbf{s}$ are the unit vectors in normal and tangential directions. Crack opening condition is denoted with $\delta = \delta_{\max}$ and $\dot{\delta} > 0$, and crack closure and reopening case is stated as $\delta < \delta_{\max}$. Thus, the traction is

$$T=\begin{cases} f_{ct}\left(1-\frac{\delta}{\delta_c}\right) & \text{for} \quad \delta=\delta_{\max} \quad \text{and} \quad \dot{\delta}>0 \\ \frac{\delta}{\delta_{\max}}T_{\max} & \text{for} \quad \delta<\delta_{\max} \end{cases}, \tag{6}$$

where f_{ct} is the critical stress associated to the cohesive element, δ_c is the effective relative displacement value beyond which complete decohesion occurs, $\delta_{\max}$ is the maximum value of the achieved effective displacement up to that instant and $T_{\max}$ is the associated traction value for maximum relative displacement.

The cohesive law and the areas that are associated to the energy dissipation are illustrated in Fig. 2. The irreversible part of dissipated

[1] Including sand, realistic packing densities for concrete can go up to 60–70%. However, this is a drastic meshing challenge in three dimensions. Higher aggregate volume fractions require smaller aggregates to be modeled explicitly, with consequently finer meshes. Hence, we only consider coarse aggregates and use a lower packing density viewing in fact the material surrounding our aggregates as a mixture of fine aggregates (that cannot be resolved explicitly) with mortar.

[2] As the name implies a representative volume is the volume over which a measurement or a calculation will yield a value that is representative of the macroscopic properties. Conventional wisdom is that at least three to five times the maximum aggregate size must be used for the specimen size in order to obtain a representative volume [40]. Since the maximum aggregate size is smaller than one-sixth of the side length of the specimen, the computer-generated mesoscale models can be considered as representative volumes.