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Pore space and brittle damage evolution in concrete

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ABSTRACT

A novel lattice model is proposed for linking experimentally measured porosity of concrete to damage evolution and the emergent macroscopic behaviour. Pore sizes are resolved by X-ray CT and distributed at lattice bonds. The mechanical behaviour of bonds is elastic-brittle with failure criterion dependent on local forces and pore sizes. Bond failures provide the only non-linear effect on the macroscopic response. Results are compared to several experimental load cases. They show good agreement of stress–strain response at lower stress levels and expected differences at peak stresses. The framework allows for future development of models with plasticity and time-dependent effects.

1. Introduction

This work is part of an ongoing research programme on the performance of cement-based materials for nuclear plant and radwaste application. In some cases such materials will have predominantly radionuclide retaining function (e.g. wasteforms, backfills) and in others predominantly structural function (e.g. Advanced Gas-cooled Reactor pressure vessel, excavation support structures). For example, a critical role of a repository for radioactive waste is to ensure minimal release of radioactive species to the geosphere over very long times. An engineering safety case would demand fundamental understanding of the long-term evolution of the macroscopic properties of these materials. Key to the retaining function of the repository is the evolution of the transport properties, such as permeability and diffusivity. These are dictated by the 3D pore space in the materials used, which is characterised by the sizes and the connectivity of the pores present (see e.g. [1]). Consequently, the evolution of the macroscopic transport properties is governed by changes in the pore space.

The ongoing programme aims at developing, and validating experimentally, predictive models for the evolution of transport properties with pore space changes. This entails a modelling approach based on a practical, sufficiently realistic and modifiable 3D pore space representation. These requirements can be met to a large extent by the so called pore network models, where the pore space is described by a system of pores with various sizes some of which are connected by throats with various sizes [2,3]. Changes in the pore space may result from chemical, electrochemical or bacterial effects as well as from mechanical damage, such as microcracking. When the pore space changing mechanism is defined, the evolution of the macroscopic transport properties can be evaluated by linking the pore network model of the pore space to appropriate model for the selected mechanism [4]. This work focuses on the mechanically induced microcracking as a pore space changing mechanism in concrete. We seek a microstructure-informed 3D model, where the pore space is explicitly represented in

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Nomenclature

c	pore radius
d	material length scale (characteristic distance for pore failure)
p	confining pressure
r	random number uniformly distributed
E	macroscopic modulus of elasticity
E_b	modulus of elasticity of lattice beams
F_i	nodal forces, $i = 1, 2, 3$
G	cumulative probability function for pore sizes
K	macroscopic bulk modulus of elasticity
L	lattice spacing in principal directions
L_1, L_2	lengths of principal and octahedral beams in lattice
M	bending moment in lattice beam
M_f	critical (failure) bending moment
N	normal force in lattice beam
N_f	critical (failure) normal force
R	radius of beam with circular cross sections
R_1, R_2	radii of principal and octahedral beams with circular cross sections
S	shear force in lattice beam
S_f	critical (failure) shear force
T	twisting moment in lattice beam
T_f	critical (failure) twisting moment
X_i	coordinate axes, $i = 1, 2, 3$
U_i	nodal displacements, $i = 1, 2, 3$
η	shear to normal strength ratio
ν	macroscopic Poisson's ratio
ν_b	Poisson's ratio of lattice beams
σ_f	critical (failure) normal stress in bond
τ_f	critical (failure) shear stress in bond
σ_{max}	maximum normal stress in beam due to bending
τ_{max}	maximum shear stress in beam due to torsion
ε_i	principal strains, $i = 1, 2, 3$
σ_i	principal stresses, $i = 1, 2, 3$
σ_0	"ideal" tensile strength (failure stress of material without defects)
ξ	non-dimensional pore size effect parameter

terms of experimentally determined pore size distribution, which can be used to inform a pore network model on changes in pore connectivity. The link between the two models is not a subject of the work and will be reported in future communications.

Discrete lattice representation of the material microstructure seems to offer the most appropriate modelling strategy for linking the mechanical behaviour to the pore network models. This is a meso-scale approach, where the material is appropriately subdivided into cells and lattice sites are placed at the centres of the cells. From one side, it is a natural solid-phase counterpart to the discrete pore networks. From the other side, discrete lattices allow for studies of distributed damage (microcracks) without constitutive assumptions about crack paths and coalescences that would be needed in a continuum finite element modelling. The deformation of the represented continuum arises from the interactions between the lattice sites. These involve forces resisting relative displacements and moments resisting relative rotations between sites. Two conceptually similar approaches have been proposed to link local interactions to continuum response. In the first one, the local forces are related to the stresses in the continuum cell (see e.g. [5–8]). In the second one, the interactions are represented by structural beam elements (or bonds), the stiffness coefficients of which are determined by equating the strain energy in the discrete and the continuum cell (see e.g. [9–12]). In both cases explicit relations between local and continuum parameters can be established for regular lattices [13]. For irregular lattices, such as those based on random Voronoi tessellation of space, such relations can be established only in an average sense [14]. Regular lattices, however, remain attractive because of the higher computational efficiency and the ability to upscale results.

Most of the previous works on lattice modelling of concrete have used a 2D lattice with hexagonal unit cell [9–12,15]. The reason is that this lattice can be made correspondent to isotropic elastic materials with Poisson's ratio of up to 1/4 in plane strain and up to 1/3 in plane stress [10,14], hence covering a relatively large class of engineering materials. The progress to 3D simulations has been hindered by the fact that the simple 3D lattices cannot be made correspondent to isotropic materials other than materials with zero Poisson's ratio. This is the case for the lattices based on HCP and FCC arrangements