Coupling between progressive damage and permeability of concrete

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Extended Summary

Quasi-brittle materials such as concrete very often fail during tension (or compression) due to localization. Micro-cracks, whose development at the beginning is almost homogeneous, start to concentrate in a region inside the material as the peak load is approached and the failure occurs with a sudden propagation of one or more macro-cracks. With the increase of diffuse cracking there is also a decrease in the stiffness of the material. In damage models this reduction of stiffness is expressed through a damage variable[1].

On the other hand, experimental results have shown that for low and intermediate stress levels, the permeability (water[2,3] or gas[4]) of concrete has significant change, and increases drastically when the load is very close to the ultimate strength of the material. From a microscopic point of view the width of the cracks is relatively small up to the peak load[5], but increases radically in the shoftening regime, causing a tremendous change in the permeability.

It is difficult to derive a proper relationship relating the variable of permeability of the material to mechanical quantity. Here we employ a lattice analysis for this purpose. The lattice which is described in this paper was used[6] in the past for the study of failure of quasi-brittle materials. It is a stiffness controlled model, where the mechanical problem is substituted by an electrical analogous, simplifying with this way the analysis by transforming it from vectorial to scalar and, as De Arcangelis et al.[7] have shown, this simplification is able to capture the most important physical aspects of the problem. The strain is substituted by the voltage, the stress by the current and the Young Modulus by the conductance.

The boundary conditions of the model are periodic in order to attain the creation of an infinite system and the partly avoidance of the boundary effects. They represent a homogeneous loading in the vertical direction: Periodicity is imposed along the boundaries parallel to vertical axis and a constant jump in voltage is applied along the two other boundaries. Every bond of the lattice behaves as a brittle material which has a conductance equal to 1 and when it reaches a threshold current it fails. This threshold differs from bond to bond following a uniform random distribution between 0 and 1 ensuring with this way the disorder of the model and, consequently, the heterogeneity of the material. For describing the state of the material at each step of damage we use the moments of the distribution of local stresses. The most important moments are these of order up to 4 because of their physical meaning: moments of order 0 represent the number of unbroken bonds in the lattice, of order 1 the average stress, of order 2 the average Young Modulus and of order 4 the dispersion of the Young Modulus.

In this article we start with the mechanical analysis and we recall the correlation between the mechanical properties: a) the average of the Young modulus, and not the number of broken bonds, is a lattice size independent parameter (i.e. the continuous variable which captures the evolution of damage in a continuum sense), b) the stress at the peak of the loading reduces with the increase of the lattice size and c) the post-peak area is strongly lattice-size dependent, a fact that was expected from experimental evidences.

The next step is to proceed to the hydraulic problem, trying to describe the relation between the permeability and the cracking mechanism. This time we use a lattice perpendicular to the mechanical one (figure 1), and solve for the hydraulic problem (assuming that when a bond fails in the mechanical problem, the bond that is perpendicular in the hydraulic problem increases its permeability). From the analysis of the corresponding moment distributions, we find first that the variable that is independent of the size of the lattice is the average permeability in the hydraulic problem. We find also that the average Young Modulus (M_{2m} in figure 2) is able to describe the hydraulic problem independently of the lattice size, which suggest that in a continuum model, the permeability should increase with damage. The permeability-stress ratio curve does not depend of the lattice size in the pre-peak area for one material and that the permeability-damage curve until the peak load is size independent and unique from experiments for different materials. This last result is consistent, from a qualitative point of view, with experimental curves obtained in Sugiyama et al.[4] and Picandet et al.[8]

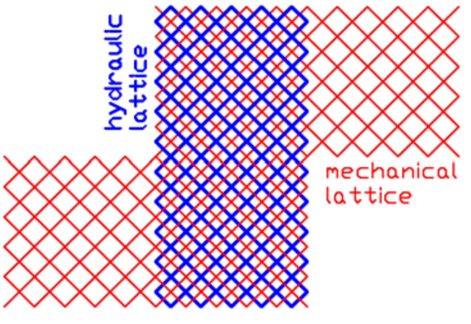

Figure 1: lattice model

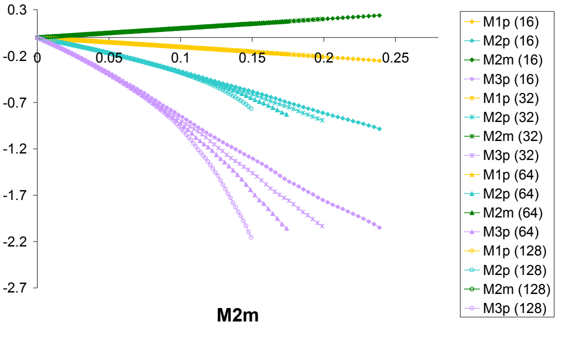

Figure 2: hydraulic moments vs. M_{2m} until the peak load

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