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Framework for a generalized four-stage fracture model of cement-based materials

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ABSTRACT

In cement-based materials the full range from brittle to ductile fracture can be achieved by changing the material structure, the loading conditions, the specimen size and/or the boundary conditions. Considering just the material, at one side of the spectrum hardened cement paste behaves brittle, whereas at the other side, new fibre reinforced cements may behave ductile. Structural conditions affect the brittleness/ductility as well, and by simply changing the loading (uniaxial tension, uniaxial and confined compression, etc.), the specimen/structure size or by changing the boundary conditions the full range from brittle to ductile response can be observed. Basically there is no difference in behaviour between the various loading cases and the same four-stage fracture process can always be identified. The four 'universal' stages are the linear elastic regime, the microcrack regime (before the maximum load is reached), the macrocrack regime (viz. the first, usually steep part of the softening curve), and the bridging stage. Microcracks are defined as cracks that can be arrested by elements in the material structure, whereas macrocracks can only be delayed/arrested by means or structural measures at a larger scale than the material structure. In this paper it is tried to develop a unified view on fracture of materials belonging to this broad class, which may be seen as conceptual framework for an all encompassing fracture model for cementitious materials.

1. Introduction

Concrete and ice, sandstone and other types of rock all have rather complex material structures. Most of these materials are built-up from different types of minerals, where the geometry of the grains may be quite regular (for example hexagonal structures of basalt, fresh-water ice), or tremendously irregular (granite, salt-water ice, cement). Ice, concrete and sandstone can be man-made. Physical processes for manufacturing these materials are sufficiently simple. This does not imply, however, that a full understanding of fracture phenomena in these materials has been achieved. As a matter of fact, over the years engineers have embraced continuum-based approaches to deal with fracture of these materials, finally ending up in non-local continuum theories, see for example in Peerlings [1]. Basic input parameters are the complete tensile stress–strain diagram including the softening regime, plus an internal length scale [2]. The latter parameter is needed for avoiding mesh sensitivity in numerical applications of such models, and until now it has not been possible to give the parameter physical meaning. In an attempt to derive the softening properties and the internal length scale using inverse analysis techniques

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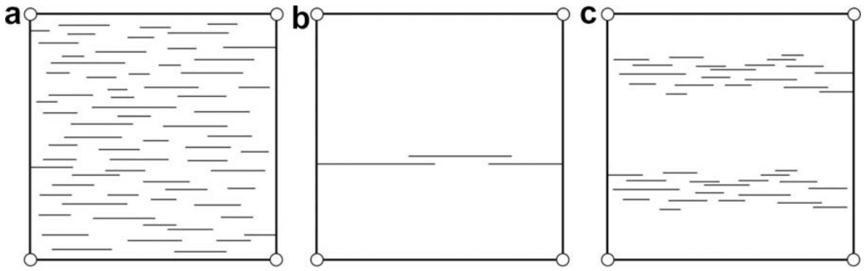

Fig. 1. Definition of (a) distributed cracking, (b) localised cracking and (c) periodic cracking, in all cases under vertical external tension.

(Kalman filter), it appeared that these parameters are confounded, and only can be determined as independent variable when more information about local strains are available, see Iacono et al. [3]. The parameters are probably confounded due to the intention to describe localization of deformations by means of strains in a continuum model. Out of sheer presumed convenience continuum theories appear to remain attractive. However, since the physics of fracture are not followed, a price has to be paid in increased complexity, confounded parameters, and, even worse, meaningless parameters. Over the years the number of parameters for describing the behaviour of geo-materials (concrete, rock, soils) has steadily increased (see for example Fig. 1 in Alonso-Marroquin et al. [4]), and it is quite debatable whether this increase has really led to a substantial improvement of the physical understanding of fracture. Most likely the phenomenological description has become better only; extrapolation beyond the investigated is not possible.

In the afore-mentioned materials, pre-critical crack growth may occur depending on the actual loading conditions, and the structure of the material at mesoscopic and smaller scales. Cracks are considered pre-critical (or stable) when the external load must increase in order to propagate them to longer lengths. Under external compression pre-critical (micro-) cracking can be quite abundant, especially when the specimens are confined, and large increase of load is needed to finally arrive at the point where pre-criticality changes into criticality. One might consider this as a phase transformation, which should be reflected in the theory used to describe said phenomena. In this respect, again, continuum theories lack the ability to describe the phase transformation, and it seems more appropriate to look to other, more suitable approaches.

Under external (uniaxial) tension, crack growth in concrete is usually assumed to be critical immediately when a certain tensile stress is exceeded. In many of the existing models this assumption is simply made, like for instance in the Fictitious Crack Model [5] and the Crack Band Model [6]. In addition these models assume that a band of microcracks advances ahead of the stress-free macrocrack, and the effective, or fictitious, crack length is elongated by the length of the microcrack zone. This should all take place in the softening regime. However, pre-critical crack growth occurs under tension, already before the maximum stress peak is reached as clarified in Van Mier [7] and can actually be traced back to the 1968 experiments of Evans and Marathe [8]. During this pre-critical process the material is 'prepared to fail macroscopically'. The pre-critical processes determine the material strength and a better understanding of these processes may eventually lead to improved models for fracture scaling in quasi-brittle disordered materials. In this paper primarily the focus will be on the pre-critical crack process, but it is attempted to place everything in a wider perspective. In the end suggestions are made for possible successful research paths that could lead to solving some of the basic open problems related to pre-critical crack growth and fracture localization. The goal of this paper is not to present a final operational model, but rather serves – hopefully – as a thought provoking means to find new ways in fracture mechanics of cement and concrete.

2. Continuum versus discontinuum

The state variables in any continuum-based theory (enhanced or classical) are stress and strain. Stress is force averaged over area, strain displacement averaged over length. During fracturing small-scaled voids open up and show localized displacements, normally referred to as crack opening and crack sliding displacements. The notion of strain becomes debatable when cracks appear and length dependency is introduced. Depending on the assumed reference length l different values of strains are calculated. Thus, during crack growth the geometrical factors in

$$\sigma = \frac{F}{A} \text{ and } \varepsilon = \frac{\Delta l}{l} \tag{1}$$

are affected, i.e. the cross-sectional area A decreases, which affect the notion of stress, and crack-opening and -sliding imply displacement. It might be possible however to consider part of the fracture process in concrete and other brittle disordered materials as a continuum process. Essential for making this assumption is that cracks are quite well distributed and do not localize into a single or a small number of crack zones of finite size (see the distinct fracture modes in Fig. 1).

Considering in more detail the fracture process in concrete, one can distinguish two distinct regimes in the entire process where continuum approaches might make sense. In those regimes the fracture process has not reached localization yet, and averaging seems possible. Based on close observations of the fracture process under mode I loading (uniaxial tension), four distinct regimes can be recognized: