Influence of internal length scales on the evolution of micro-cracking in fiber-reinforced composites

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ABSTRACT

Composite materials made of strengthening fibers embedded in brittle matrices (e.g., fiber-reinforced concretes) usually exhibit failure mechanisms characterized by an initial stress-hardening phase, associated to micro- and multi-cracking within the matrix, and a following softening stage, associated to the development of macro-cracks. The bridging effect of fibres plays a key role in this process, conferring improved ductility to the composite.

In the present communication, a variational model is proposed where the composite is schematized as a mixture of two phases coupled by elastic bonds. The two phases account for a brittle material and a ductile elasto-plastic material, representative of matrix and fibers, respectively. According to the phase-field approach to fracture, a damage internal variable accounts for the opening and propagation of fractures in the brittle matrix, and a plastic strain field describes the evolution of inelastic deformations within the reinforcement phase. Once proper energy densities are associated to the two phases and the bonds, the evolution problem is formulated as an incremental energy minimum problem. Analytical estimates and numerical solutions are determined which show the model capability of describing the two main stages of the evolution, that is, the micro-cracking patterning in a regime of stress-hardening, and a subsequent macro-crack opening with progressive stress-softening.

The damage and plastic energies of the two phases incorporate non-local contributions, which introduce internal length scales. The internal length of the brittle phase is related to the size of the process zone accompanying the fracture process, and it depends on the size of the particles that the matrix is made of. The internal length of the reinforcement phase accounts for the size of the plastic localization zone that forms when macro-cracks develop, and it is dependent on the length of the fibers. A third characteristic length arises from the elastic energy coupling the displacement fields of the two introduced phases. It controls the distance between adjacent micro-cracks and it depends on the size of matrix-to-fibers stress transfer zone, which forms over each micro-crack. Attention is focused on the influence of these three characteristic lengths on the process of micro-crack patterning and on the evolution of macro-fractures. Several cracking scenarios are investigated, depending on the different values assigned to the internal lengths.