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Tailoring strain-hardening cementitious composite repair systems through numerical experimentation

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ABSTRACT

Innovative cement-based repair materials may require different procedures for application in comparison to standard repair requirements. Before their field application, a proper protocol should be established. Apart from laboratory experiments, numerical simulation can be of great use. Herein, a lattice type model is used to simulate fracture performance of fiber reinforced repair material – strain hardening cementations composite (SHCC) and its performance in the repair system. Repair material was first tailored through numerical testing in a single fiber pullout test and a direct tension test. Further on, structural behavior of the repair system and impact of initial defects in the mortar substrate (reflective cracking) was examined. The influence of fiber addition, different simulated substrate roughness and interface properties between new and old material on the performance of the repair system is investigated. Fracture propagation and sequence of crack development obtained by simulation is compared to experimental results. The numerical study gives insight into the benefits of distributed microcracking and high ductility of the fiber reinforced system over localized cracking and inherent brittleness of a non-reinforced repair system. It is envisioned that this approach can be used to tailor the properties of the repair system for specific applications, resulting in more reliable and durable concrete repairs in the future.

1. Introduction

Durability of concrete repairs, including all types of repairs and application of different materials, often shows problems [1]. Most of the past efforts focused either on reducing free shrinkage of repair material, increasing its compressive/tensile strength, or increasing bond strength between a repair material and a concrete substrate. However, all these attempts resulted in only marginal improvements as they did not address inherent behavior of concrete as a brittle material [2]. Furthermore, brittleness is even more pronounced in high strength concrete, as it is more prone to cracking. In order to address brittleness as an intrinsic issue of repair systems, Li et al. [3] developed an ultra-ductile fiber reinforced composite called strain hardening cementitious composite (SHCC).

SHCC is characterized by formation of narrow microcracks and strain hardening behavior. Multiple cracks are beneficial for relief of stresses induced by deformational incompatibility between the new and old material. Moreover, high ductility of this material, achieved through dense microcracking, showed to have great potential in effectively suppressing crack localization and interface delamination between the old and new material in concrete repair applications [2–4]. Although very promising, a procedure for practical application of this material is not yet established. Use of numerical testing, supported with experimental observations, can give insight in the influence of parameters that are commonly addressed when designing concrete repairs.

Here, a lattice type model [5] is used to simulate fracture performance of fiber reinforced repair material. Simulation of fiber reinforced concrete with a lattice type model was already applied by Bolander et al. [6,7], where reduction of the shrinkage cracks with the addition of fibers was investigated. The presented model is based on the principle of embedding discrete fibers in a random lattice mesh representing the material matrix [8]. Different types of fiber reinforcement, including wood fibers, can be simulated [9]. Herein, the influence of addition of polyvinyl alcohol-PVA fibers is examined and compared to non-reinforced material.

SHCC was first designed through numerical testing in a single fiber pullout test and a direct tension test. In this way, input values for the mechanical properties of the lattice elements are

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determined. The influence of different material laws for the fiber/matrix interface elements on composite behavior and achieved crack density is investigated and compared to the experimental results [10].

Once local material properties for the simulated repair material are defined, structural behavior and debonding tendency of the repair system is investigated. Cracking or debonding of the overlay reduces the load-carrying capacity of the overlay system and allows water and other hazardous substances to penetrate into concrete. Predicting and quantifying the performance of overlay will, therefore, enable more reliable estimation about efficiency and service life of the repair system. It is well recognized that surface preparation and interface status between SHCC and substrate concrete are important parameters when designing a repair system [11–13]. Therefore, the influence of these parameters on the resulting fracture performance of the repair system, both for reinforced and non-reinforced repair material is investigated. Since existing cracks or joints in the old material are initiation points for crack localization in repair material (reflective cracking), the possibility of suppressing these cracks is also investigated.

2. Lattice model

Fracture processes of cement-based materials can be simulated with lattice models [8,14]. In these models, the material is discretized as a network of truss or beam elements connected at the ends. Usually all the single elements have linear elastic properties. In each loading step, an element that exceeds the limit stress or strain capacity is removed from the mesh. The analysis procedure is then repeated until a pre-determined failure criterion for the simulated specimen is achieved. In this way realistic crack patterns can be obtained. Further on, although each element has brittle behavior, structural softening and ductile global behavior can be simulated.

The procedure to generate the network is as follows:

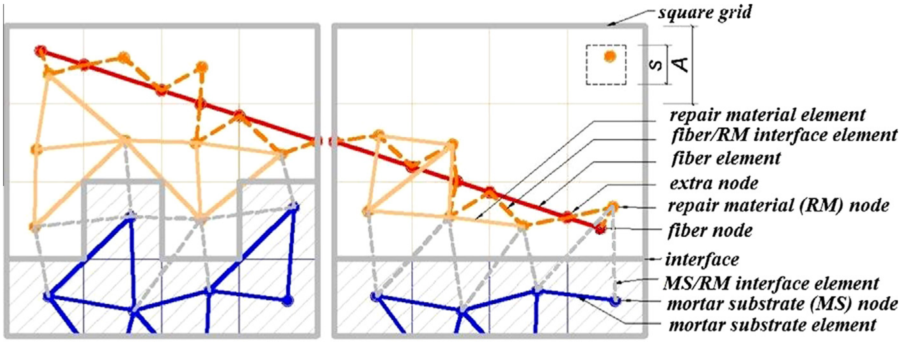
- A cubical grid is chosen (square for 2D lattice).
- In each cell of the square (cube for 3D lattice), a random location for a lattice node is selected. First the nodes are randomly positioned inside a sub cell of size *s* in a regular grid with size *A* (Fig. 1). The ratio *s/A* is defined as randomness of a lattice and here it is set to be 0.5. This means that some disorder is built into the lattice mesh itself.
- Always the three nodes (four nodes for 3D) which are closest to each other are connected by beam elements using Delaunay triangulation. Each node of the 3D system has 6 degrees of freedom (3 translations and 3 rotations).
- The beams which belong to each phase are identified by overlapping material layers (i.e. concrete/mortar substrate and repair material) on top of the lattice. Interface elements are generated between substrate nodes and repair material nodes. In Fig. 1, generation of interface elements for the smooth and rough (grooved) substrate surface is presented.
- Fiber elements are added in the repair material according to a chosen volume content (2% by volume in case of SHCC), fiber length and diameter. The location of the first node of each fiber is chosen randomly in the specified volume and a random direction is defined which determines the position of the second node. If the second node is outside of the mesh boundary, then it is automatically cut off and accounted for in order to ensure preservation of prescribed volume content.
- Extra nodes inside the fibers are generated at each location where the fiber crosses the square (in 3D cubical) grid.
- Fiber interface elements are generated between fiber nodes and the matrix nodes in the neighboring cell. Also, the end nodes of the fibers are connected with an interface element to the matrix node in the cell where the fiber end is located (Fig. 1).
- Different mechanical properties are ascribed to the elements of the repair material, fibers and fiber/repair material interface, as indicated in Table 1. Fiber properties are adopted from literature [15]. Repair material and fiber/repair material interface properties are fitted from simulated pullout test and direct tension test. These are compared to experimental results obtained at specimens' age of 28 days [2,10] (see Section 3).
- An element can fail either in tension or in compression, when the stress exceeds its strength. For the fracture criterion, only axial forces are taken into account to determine the stress in the beams.

In all simulations presented herein, linear dimension of the cubical grid used for mesh generation (see Fig. 1) is 1 mm. Values for the mechanical properties for interface elements which connect repair material and mortar substrate (Table 1) are assumed values. As the interface is usually the weakest zone in the system, lower properties are ascribed to elements which characterize this zone. For simplicity, it was also assumed that the mortar substrate has the same mechanical properties as the repair material matrix. Although in real repair systems this is not the case, here it was done in order to avoid additional influence of this parameter on the response of the system.

3. Tailoring repair material and discussion

3.1. Pullout test

Proper design of strain hardening behavior of SHCC is achieved through tailoring of the matrix/fiber interface properties. When the crack starts opening, fibers are activated, take over the tensile force over the crack surfaces and, along their interface, transfer it into



Rough surface

Smooth surface

Fig. 1. Two-dimensional overlay procedure for generation of the lattice model for the grooved and smooth surface profile.