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Numerical simulation of ductile fiber-reinforced cement-based composite

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ABSTRACT

Strain Hardening Cement-based Composite (SHCC) is a type of High Performance Concrete (HPC) that was developed to overcome the brittleness of conventional concrete. Even though there is no significant compressive strength increase compared to conventional concrete, it exhibits superior behavior in tension. The primary objective of the presented research is to develop a constitutive model that can be used to simulate structural components with SHCC under different types of loading conditions. In particular, the constitutive model must be efficient and robust for large-scale simulations. The proposed model, based on previous research Vorel and Boshoff (2012), for plane stress is outlined and the further focus of this paper is on the mesh objectivity of the model. It is shown to be mesh size independent.

1. Introduction

At the beginning of the 21st century, civil engineers more than ever faced the often-contradictory demands for designing larger, safer and more durable structures at lower cost and shorter time. Concrete has been used for many centuries as a safe and durable building material. Two of the main advantages of concrete are its high compressive strength and that it can be cast on the construction site into a variety of shapes and sizes. The most prominent disadvantages of concrete and other cementitious materials are their brittle failure behavior in tension and the low tensile strength. The low tensile strength is usually compensated for with steel reinforcement, but wide cracks leading to the corrosion of the steel reinforcement still occur during the normal use of concrete [1]. These cracks lead to durability problems and cause structural degradation to occur more rapidly.

Fiber Reinforced cement-based composites (FRC or FRCC) is a large group of composites with variety of properties. The reason for adding fibers is to overcome the brittleness of the concrete by improving the post-cracking behavior and enhancing ductility. The paper deals with the group of Strain Hardening Cement based Composite (SHCC), a type of High Performance Concrete (HPC), that exhibits excellent mechanical behavior showing tensile strain hardening and multiple fine cracks [2,3]. It has been shown to reach a tensile strain capacity of more than 4% during a strain hardening phase [2,3] caused by the fine, closely spaced multiple cracks with crack widths normally not exceeding 100 μm [2,3]. These fine cracks, compared to large (greater than 100 μm) localized cracks found in conventional concrete, have the advantage of increased durability. For a further discussion of the mechanical properties of SHCC, the reader is referred to [4,5].

Several scholars have simulated SHCC mechanical behavior with the Finite Element Method (FEM) [6–9], Extended Finite element Method (XFEM) [10] or lattice model [11,12]. Kabele [9] formulated a model to simulate the mechanical behavior

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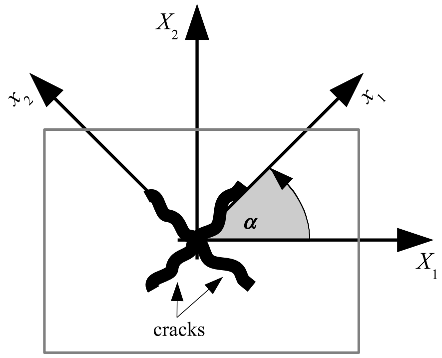

Fig. 1. Coordinates and transformation angle.

of SHCC using a smeared crack approach. Despite acknowledging that a discrete cracking model would be best for the final localizing crack, Kabele decided to use a smeared cracking approach for the localization. This is due to the uncertainty of the position of the final localizing crack. Another model was proposed by [8]. This model was created to simulate the behavior of SHCC under cyclic loading to test the improvement in structural response if SHCC elements are used to dissipate energy during earth-quake loadings. Computational modeling of SHCC was also performed by [13] who used an embedded discontinuity approach for the final material softening. This method would have the same kinematic characterization as one obtained with interface elements for discrete cracking, but does not require remeshing procedures. Their conclusion was that it did not simulate the experimental results of SHCC satisfactorily due to the simplicity of the model. Boshoff [6] created a simple damage mechanics based model for the tensile behavior of SHCC. This was implemented numerically using the FEM. Even though numerous shortcomings still exist, the model showed relatively good results. Remaining issues include an unresolved mesh dependence and the under prediction of the deformation when analyzing a structure with a strain gradient. Radtke et al. [10] employed discrete fiber distributions taken into account by employing the partition of unity property of finite element shape functions without explicitly meshing them. In this approach the definition of the constitutive behavior of the matrix material, the fiber material and the fiber-matrix bond is assumed. Although this method showed satisfactory results and versatility, the simulated specimens must be limited in size as the method would be too computationally demanding for real world structures.

The primary objective of the presented research is to develop a constitutive model that can be used to simulate structural components with SHCC under different types of loading conditions. In particular, the constitutive model must be efficient and robust for large-scale simulations. The proposed model, based on previous research [14,15], for plane stress is outlined and the further focus of this paper is on the mesh objectivity of the model.

The paper is organized as follows. The general features and definitions of the model are described in Section 2. Sections 3 and 4 deals with the finite element simulations and results of studied experiments. Finally, the concluding remarks and discussion are provided in Section 5.

In the following sections the tension and compression related parameters and variables are denoted by subscripts starting with t and c, respectively. The superscript $\cdot^*$ is utilized to characterize the driving parameters for unloading and reloading when no stress state change occurs, while $\cdot^{**}$ denotes the driving parameters when stress state change takes place.

2. Numerical model definition

In this section the main features of the utilized numerical model are described. To model the specific behavior of SHCC in tension, the application of classical constitutive material models used for quasi-brittle materials is not straightforward. The proposed numerical model is based on a rotating crack assumption to capture the strain hardening and softening, the multiple cracking, the crack localization and multiple orthogonal crack patterns [16]. A schematic representation of orthogonal cracking using the rotating crack model is shown using global and local axes in Fig. 1. In heterogeneous materials where micro-cracking occurs prior to the formation of a macro-crack, the rotating crack model may be more realistic than the fixed crack model. Micro-cracks are formed orthogonal to the major principal stress when the tensile strength is first violated. However, upon rotation of the principal stress axes new micro-cracks arise in the "rotated" direction and it is most likely that upon termination of the stress rotation, the latter micro-cracks will grow into macro-cracks. This justifies the choice of a rotating crack model from a physical perspective. A complete description of the rotating crack model can be found, e.g., in [17].

The presented model is implemented in the open source finite element code OOFEM [18] for plane stress elements using a coaxial rotating crack method (RCM) with two orthogonal cracks as described in [8]. This numerical approach is classified as the smeared crack model with the softening defined by means of the cohesive crack and overlapping crack model [19].

The rotating crack model evaluates a given strain state and generates the inelastic strain in the principal directions of the strain. Therefore, it is inevitably required to introduce a transformation tensor ($[\mathsf{T}]_\varepsilon$, $[\mathsf{T}]_\sigma$) interconnecting a global strain