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An effective discrete model for strain hardening cementitious composites: Model and concept

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ABSTRACT

Strain hardening cementitious composite (SHCC) are materials exhibiting high deformation capacity and excellent crack control. In applications where SHCC is employed to enhance durability, information on the crack width and spacing under loading is important. In conventional finite element analysis, the material is commonly modeled as a continuum with tri-linear tensile behavior, which cannot capture the crack pattern. Here an efficient discrete model for SHCC is proposed to address such an issue, with the use of continuum element for matrix damage/cracking, truss element for fiber bridging effect and interface element for matrix-fiber interaction. Appropriate constitutive laws are assumed for these elements and the parameters are calibrated from direct tensile test. The validity of the model is shown by analyzing a tensile specimen and the realistic multiple cracking process of SHCC is captured. Through a systematic parametric study, the effects of important model parameters on the tensile behavior of the composites are assessed. The proposed model is further improved to accurately reproduce the evolution of crack pattern, including average and maximum crack width, crack density and crack width distribution. Efficient and accurate, the model can be used for analysis of SHCC members under bending, restrained shrinkage or subject to reflective cracking.

1. Introduction

Through proper matrix design, fiber selection and interfacial treatment, strain hardening cementitious composites (SHCC) with tensile failure strain up to several percent (often 3–5%) can be designed. In such materials, strain hardening is accompanied by the formation of multiple cracks with opening of 50 μm or below. With high ductility and excellent crack control, SHCC can be employed to enhance the deformation capacity, energy dissipation, damage tolerance as well as durability of structural components. The ductility of the material is important for deformation capacity and damage tolerance. While for durability enhancement, an important design parameter is the crack opening on the member surface, which governs the penetration of water and other chemicals such as chlorides.

When tensile cracking occurs in the SHCC matrix, the stress released by the cracked matrix is taken up by the fiber. The fiber bridging law guarantees the multiple cracking behavior of SHCC if it satisfies both strength and energy criteria. The strength criterion is that the maximum bridging stress should be higher than the first cracking strength of matrix. The energy criterion is that the complementary energy of fiber bridging law is larger than the fracture energy of matrix, which would lead to steady state crack propagation with a large part of the crack profile staying at constant (and small) opening. The details of these two criteria can be found in Li and Leung [9] and Li [8]. To find the multiple cracking pattern, earlier work (e.g., [28]) considers the random distribution of material property, especially the matrix strength, so cracking occurs subsequently at different locations. However with this approach, the distribution of the simulated crack spacing is different from that observed in experiments. As shown by the pioneering work of Aveston and Kelly [1], the spacing of multiple cracking is governed by the stress transfer distance from a crack beyond which the matrix strength is reached again. To find this distance, the interaction between fiber and matrix needs to be analyzed. Conventional finite element analyses based on continuum models do not take such interactions into consideration. Instead, the composite is modeled with continuum element following various kinds of tensile constitutive laws. For example, the homogenization based constitutive law ([14,3]) follows a tri-linear tensile behavior (linear elastic stage, strain hardening stage and strain softening stage, as shown in Fig. 1(a)) idealized from direct tensile tests. This approach can predict the load vs. deformation relation as long as each element covers a few cracks under

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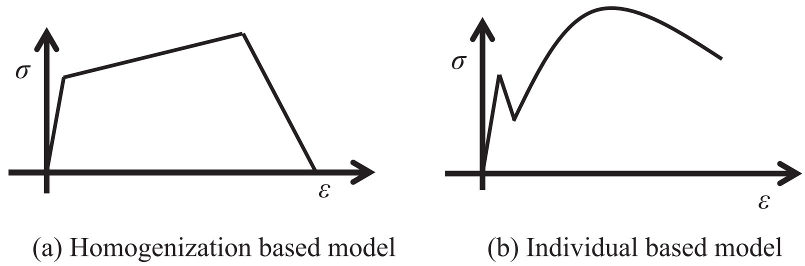

Fig. 1. Constitutive law of conventional model for SHCC.

relatively low stress gradient, so the 'average' composite behavior is properly represented. However, the analysis cannot provide any information on crack spacing or crack opening. Moreover, when the stress gradient is high and thus deformation is not homogeneous, e.g., when SHCC is employed to resist concentrated stress or shear, the accuracy of the continuum approach is doubtful. Kabele [15], Kabele [16] and Yang and Fischer [29] proposed an individual crack based constitutive law for SHCC, which is as shown in Fig. 1(b). In this approach, the bridging stress vs. crack opening relation is first determined from theoretical derivation or experimental testing of a notched tensile specimen. For a particular element, the post-cracking stress vs. strain relation can then be obtained by simply dividing the crack opening by the element dimension perpendicular to the crack (Note: in this case, as shown in Fig. 1(b), there is a post-peak stress drop due to matrix cracking followed by stress increase with further crack opening as loading is picked up by the fibers). According to Kabele [15], this model can improve the result for non-proportional loading (e.g., shear in the case studied). However, with the model of Kabele [15] one crack will form in each element as long as the tensile strength is reached, so crack spacing is determined by the mesh size. For correct analysis of the crack pattern and crack development process, a priori information on the crack spacing is therefore required to come up with the proper mesh size. The concepts of Kabele [15], i.e., a priori determined crack spacing and with bridging force exerted along crack surface, is similar to smeared model proposed by Belletti et al. [2] for reinforced concrete. As an alternative approach, Yang and Fischer [29] and Kabele [16] considered heterogeneity of material property (i.e., variation of strength and crack bridging behavior among different sections) based on experimental results and imposed a minimum crack spacing condition so cracks are sequentially formed at random location under increased loading. Recently Huang and Zhang [33] implemented a similar technique, i.e., randomness of matrix and fiber bridging law as well as minimum crack spacing condition, in the framework of eXtended Finite Element Method or XFEM [25], with cohesive zone model adaptively embedded in the model.

There are also some advanced models for SHCC which attempts to model the random fibers directly and consider the post-cracking interaction of each fiber with the matrix explicitly for multiple cracking analysis. These include the lattice model [34,11] and rigid body spring model [19,17]. While these models have the potential to capture how the actual stress transfer mechanism between fiber and matrix affects the multiple cracking behavior, there are many degrees of freedom in the model which makes the computation very time-consuming. These approaches are therefore inappropriate for analysis of structural members.

The multiscale framework proposed by Kabele [35] and lattice model proposed by Spagnoli [23] are two other approaches for the modeling of SHCC. While they are computationally more efficient than the advanced models described above, the stress transfer between fiber and matrix is not explicitly considered as fiber bridging stress is applied directly on the crack surface.

Based on the above discussion, there is a need for a new model, which can not only calculate crack spacing and width in SHCC, but with sufficient computational efficiency for analysis of structural members. Thus in this paper, a new discrete model for SHCC material is proposed to fill this gap. After a crack forms in the matrix, the crack spacing (and opening) between this crack and the nearby possible crack is governed by the stress transfer between fiber and matrix. To consider such stress transfer explicitly in numerical analysis, we model matrix, fiber and fiber/matrix interface separately with three different types of elements, including continuum element (which can undergo cracking) for matrix, truss element for bridging fiber and interface element for stress transfer. In the following, the modeling concept is first described in detail. In reality, there are many fibers bridging the crack and interfacial stress distribution is very complicated. Instead of modeling the details of every individual fiber (length, orientation and location) and the fiber/matrix interaction (bond and friction), the current study aims at developing equivalent truss and interface elements that can represent the overall effect of these fibers, which thus reduces the computational effort. Corresponding to each matrix element, only one truss element and one interface element will be employed. The model will then be simple and efficient enough for the analysis of structural members. A major challenge in this work is to determine the constitutive behavior of the equivalent elements, which cannot be directly measured. In view of the complex stress transfer mechanisms, purely theoretical derivation is also very difficult. A physically based phenomenological approach will hence be adopted. Based on previous theories, the form of the constitutive behavior is first obtained. Material parameters for the constitutive relation are then determined from results of direct tensile test of SHCC. The proposed discrete model is validated by analyzing a direct tensile specimen and the result is compared with that of test. Then a systematic parametric study is performed to study the sensitivity of SHCC's performance to the material parameters. Based on the finding of the parametric study, the proposed model is further improved to enable more accurate prediction of experimental results on crack pattern and crack width.

2. Physical process of multiple cracking and basic modeling concept

According to Li and Leung [9], brittle matrix reinforced with short random fibers could show multiple cracking if properly designed. In the last two decades, ECC (Engineered Cementitious Composite) [27] and UHPFRC (Ultra High Performance Fiber Reinforced Concrete) materials demonstrating strain hardening and multiple cracking behavior have been studied by many researchers and applied in civil engineering projects. To facilitate their wider application, a proper model for their multiple cracking behavior is desired.