Initiation and development of cracking in ECC materials: experimental observations and modeling

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ABSTRACT: Applications of fiber reinforced engineered cementitious composites (ECC) and other strain hardening cementitious composites (SHCC) require information on their material properties for structural purposes as well as for durability. The distinctive material properties of ECC and other SHCC materials are the tensile stress-strain relationship and the cracking characteristics including crack width and spacing prior to localization of cracking. The investigations presented in this paper will focus on these distinctive features and aim at developing tools to predict and design for specific composite behavior.

The initiation and development of cracking are principal mechanisms in the tensile deformation behavior of ECC and other SHCC materials. In this paper, the parameters affecting the initiation and propagation of cracking and the fiber bridging stress-crack opening relationship are investigated. Furthermore, the observations will form the basis for calibration of a plasticity based damage mechanics model for ECC.

It is found that the size and distribution of flaws in the cementitious matrix and the range of fiber bridging-crack opening characteristics throughout the composite material are the governing parameters for the tensile stress-strain response. Particularly important for the durability of structures containing ECC is the evolution of crack widths under increasing tensile loads up to the tensile strength of the material. The experimental data and analytical tools presented in this paper will provide detailed information on this particular feature of ECC materials.

1 INTRODUCTION

Fiber reinforced concrete can be categorized into conventional Fiber Reinforced Cementitious Composites (FRCC) and Strain Hardening Cementitious Composite (SHCC). The former shows a tension softening behavior after first cracking, whereas the later develops multiple cracking and a strain hardening behavior in tension. Compared to plain concrete and conventional FRCC, SHCC shows a significant improvement in ductility. SHCC characteristics at low volume fraction of discontinuous, randomly oriented fibers have been achieved in Engineered Cementitious Composites (ECC) such that industrial application of this composite material can be economically feasible. For better understanding the properties of this promising material, a significant amount of research effort has been focused on micro mechanics of the composite, and various models have been established to characterize the fiber bridging behavior leading to such composite properties. An analytical model that accounts for the multiple cracking of short randomly distributed fiber composites was introduced by Li & Leung (1992) under the assumption of no fiber rupture in the fiber bridging-crack opening process. Later, Maalej et al. (1995) extended the model to account for the possibility of fiber rupture, which is referred to as fiber pullout and rupture model (FPRM). However, these analytical models assume a deterministic tensile rupture strength of the fibers bridging a crack. Maalej (2001) proposed a model to predict the bridging stress-crack opening relationship (hereafter abbreviated as σ_B -δ curve) – a fundamental material property necessary for the analysis of steady state cracking in short random fiber composites. The model was derived for fibers having a statistical tensile strength distribution. For ECC to develop multiple cracking in the strain hardening stage, the flaw size distribution of the matrix also plays an important role. Wu & Li (1995) predicted the multiple cracking process of short random fiber reinforced brittle matrix composites through Monte Carlo simulation of the flaw size distribution. Furthermore, Wang & Li (2004) tailored the material including pre-existing flaws in Engineered Cementitious Composites (ECC) by introducing artificial flaws and greatly enhanced the multiple cracking behavior and ductility of the composite in uniaxial tension.

The above mentioned research efforts, which account for the influences of the distribution of fiber tensile strength and matrix flaw size, are invaluable in combining the micro mechanics of fiber bridging with random properties of fiber and matrix. In this paper we examine directly the experimentally obtained σ_B -δ curve, and utilize this information as a parameter to simulate the multiple cracking and strain hardening behavior of ECC in uniaxial tension. In this way, parameters that are difficult to realistically predict, such as randomness in fiber tensile strength, matrix flaw size distribution, fiber matrix interfacial bonding, and other factors are inherently included. Based on the experimentally obtained data of the fiber bridging stress-crack opening relationship, a simulation method is proposed and compared to experimental test results.

2 CONCEPT

The load-deformation behavior of ECC materials was investigated with respect to the initiation and propagation of cracking as well as the formation of multiple cracking.

The influence of the initial flaw size, a_0 in a typical ECC material has been investigated by Dick-Nielsen et. al. (2006) by use of a semi-analytical approach. Here, simulations have been performed for infinite sheets containing initials flaws with different realistic lengths.

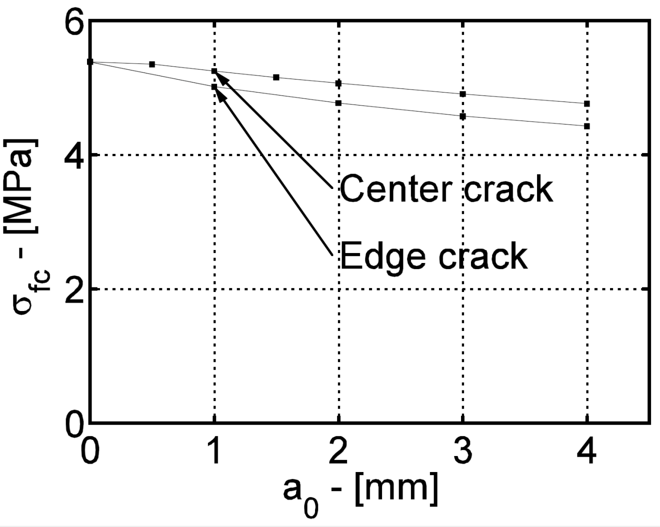

Figure 1a Relation between first crack strength, σ_{fc} and initial crack length, a_0.

The results are shown in Figure 1 for center cracks and edge cracks respectively. The entire length of the center flaw is denoted $2a_0$ while the entire length of the edge flaw is denoted a_0. Due to this definition flaw lengths in the two situations can be directly compared.

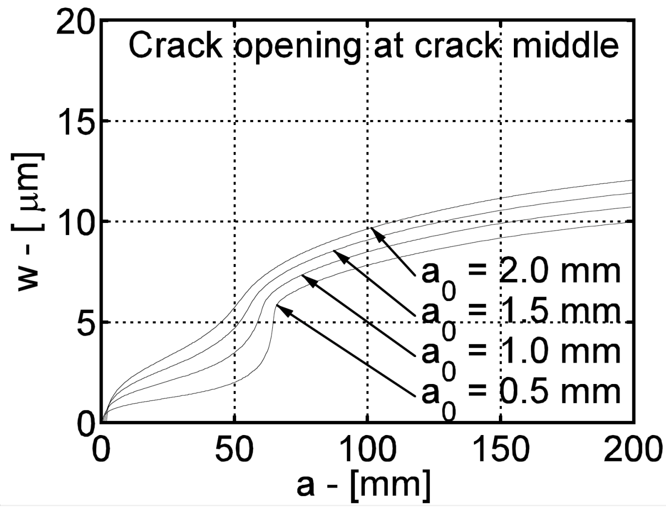

Figure 1b Center crack opening w and matching total crack length, a.

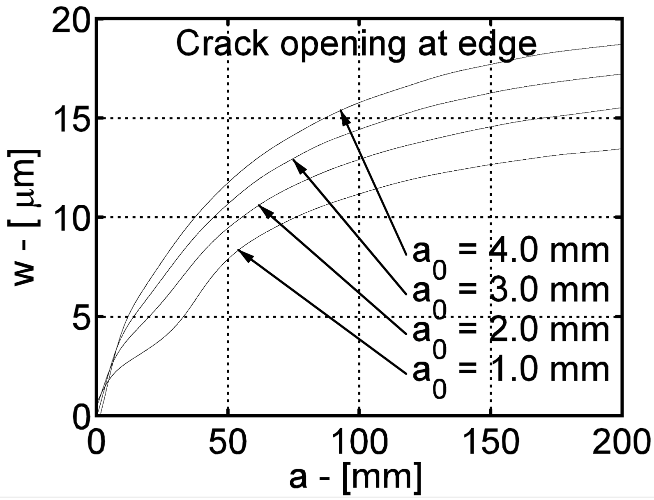

Figure 1c Edge crack opening w and corresponding total crack length, a.

Increasing length of the initial stress free flaw resulted in a decrease of the first crack strength (see Figure 1a). For center cracks the decrease in first crack strength is weak while it for edge cracks is more pronounced. For crack lengths, a smaller than 200 mm the maximal crack opening found in the simulations was less than 20 μm independent of crack position and initial flaw size. At no time during these crack propagations was the process zones fully evolved.

The particular SHCC investigated experimentally in this study was an Engineered Cementitious Composite (ECC) reinforced with PVA (Polyvinyl Alcohol) fibers (2.0 Vol-%). The PVA fibers have a nominal tensile strength of 1600 MPa and are 8 mm long with a diameter of 39 μm. The ECC mix proportions are listed in Table 1, with proportions of ingredients given by ratio of weight, except for the fibers, which are quantified by volume fraction.

Table 1 Mix proportions of PVA-ECC

Cement	Fly Ash	Sand	Water	SP	PVA Fiber (Vol. %)
1	2	1.4	1	0.023	2

The fiber reinforcement was added to the cementitious matrix during the mixing procedure and the composite was cast into blocks (3in x 4in x 16 in) from which the test specimens were cut into the shape shown in Figure 2 (Yang and Fischer, 2006). The specimens are notched on all sides to facilitate the formation of a single crack. Ideally, a single crack should be generated at the notch when a tensile load is applied and the crack opening is measured using a clip gauge.

Plan view Side View

Figure2 Specimen dimensions

The stress is calculated by normalizing the tensile load by the cross-sectional area at the notch and is plotted against the measured crack opening to obtain the σ_B -δ curve. To check whether there is indeed only a single crack at the predefined crack location, the test is terminated immediately after the

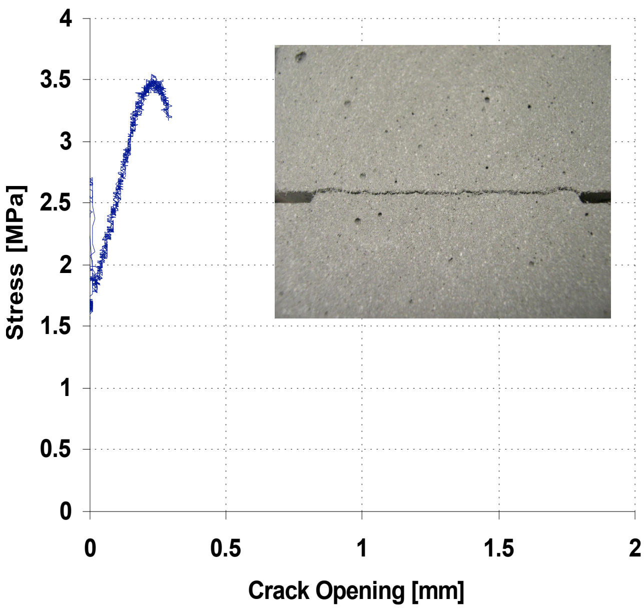

Figure 3 σ_B -δ curve of a single crack

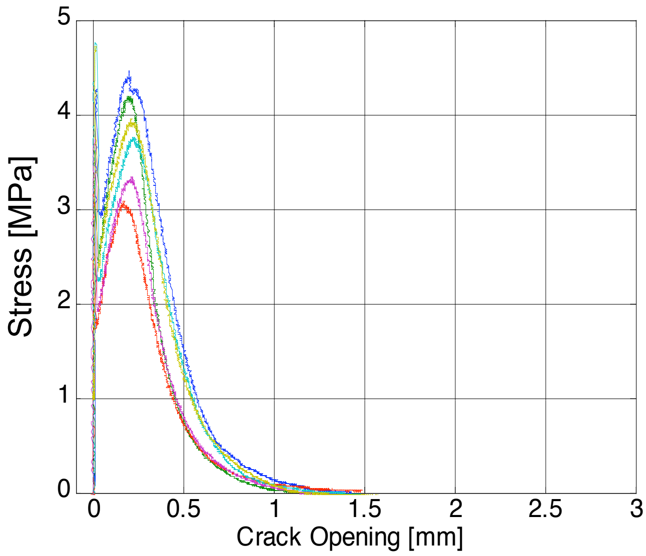

Figure 4 σ_B -δ curves of specimens

load has reached the peak level, and the specimen is cut vertically along the center line of its thickness to visually inspect the crack formation. Figure 3 shows typical observations of cut specimens with a single crack and the corresponding σ_B -δ curve.

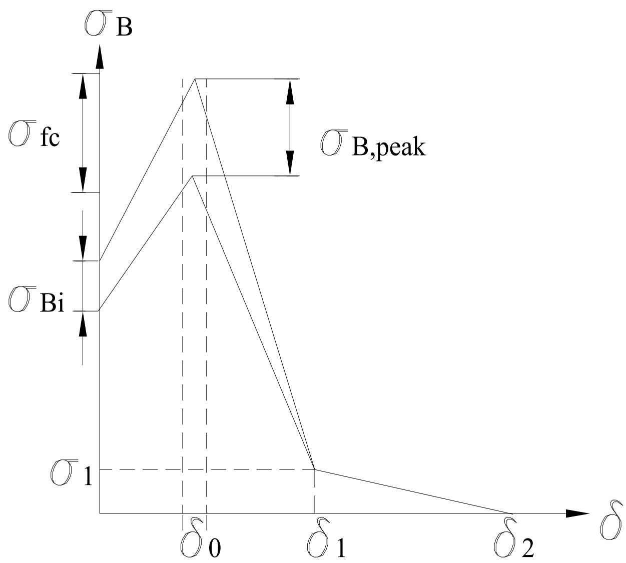

Figure 5 Envelope of the simplified σ_B -δ curves

The tensile tests were carried out on specimens that were cured in air for 28 days. Figure 4 shows the σ_B -δ curves obtained. From these curves it can be observed that while the ultimate fiber bridging stress has relatively large variability, the crack opening at the peak load remains relatively constant.

Based on the range of fiber bridging stress-crack opening responses obtained from the experimental investigation, a tri-linear simplification as shown in Figure 5 is chosen to represent the experimentally obtained responses. To account for the variability in the σ_B -δ curve, a range in characteristic composite parameters is assumed in the model based on the experimentally obtained data. The parameters that affect the behavior of the composite are the first cracking strength σ_{fc}, the peak bridging stress $\sigma_{B,peak}$, the crack opening δ_0 at peak bridging stress, and the fiber bridging stiffness K_f. These parameters may vary randomly within the experimentally defined range and will inherently account for the variability in fiber tensile strength, orientation, interfacial bond characteristics, and matrix flaw size distribution. The simulation model for the composite stress-strain behavior developed in this study will include potential multiple cracking and strain hardening features of the ECC in direct tensile loading. For general applicability of the model to SHCC materials as well as tension softening FRCC, model parameters can be adjusted to experimental data obtained for the fiber bridging stress-crack opening relationship of other FRCC materials.

During the displacement controlled deformation process of the composite, the tensile specimen initially behaves like a spring with an effective stiffness K_m of the un-cracked composite. At increasing deformations, the tensile load increases until the first crack forms at the largest flaw and lowest first cracking strength in the specimen. After the first tensile crack is formed, the cracked composite is represented by inserting a second spring element with a stiffness corresponding to the fiber bridging stiffness K_{f1}, as shown in Figure 6. The load will subsequently drop to a value where force equilibrium between the fiber bridging section and adjacent uncracked composite section is achieved. When the induced tensile deformations in the composite are further increased, the load will again increase with a modified total stiffness K until the tensile stresses are sufficient to cause the formation of a second tensile crack in the composite. This process is continued and multiple cracking can initiate until the tensile stress reaches the lowest peak bridging strength as defined by the parameter envelope (Figure 5). At this point, localization of cracking occurs and the composite fails in a tension softening manner.

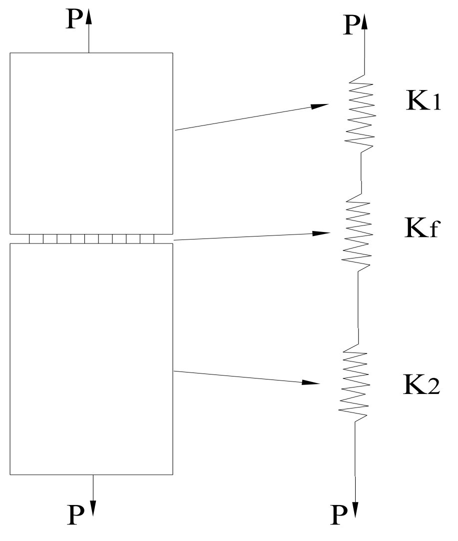

Figure 6 Equivalent spring system

The maximum number of potential cracks in a given composite is governed by the specimen length and the minimum crack spacing x_d, which has been theoretically derived[5] for the case of random short fiber reinforced composites. A crack spacing between x_d and $2x_d$ is expected at crack saturation. However, due to the variation of matrix properties, fiber matrix interfacial bonding, and fiber distribution, the observed minimum crack spacing often exceeds twice the derived minimum crack spacing. For PVA-ECC with preexisting flaws, a minimum crack spacing of 1.7 mm to 2.5 mm at crack saturation was reported[7].

Experimental results of the stress-strain response of PVA-ECC show a minimum crack spacing of 2 mm, which is adopted as a parameter for the simulation model presented in this paper. At a given specimen length and minimum crack spacing, the maximum number of potential cracks and their locations are identified along the specimen. Then, a randomly selected σ_B -δ curve from the envelope (Figure 5) characterized by its associated parameters (see e.g. Table 2) is assigned to each potential crack location and the simulation of the uniaxial tension test can be run using the procedure described above.

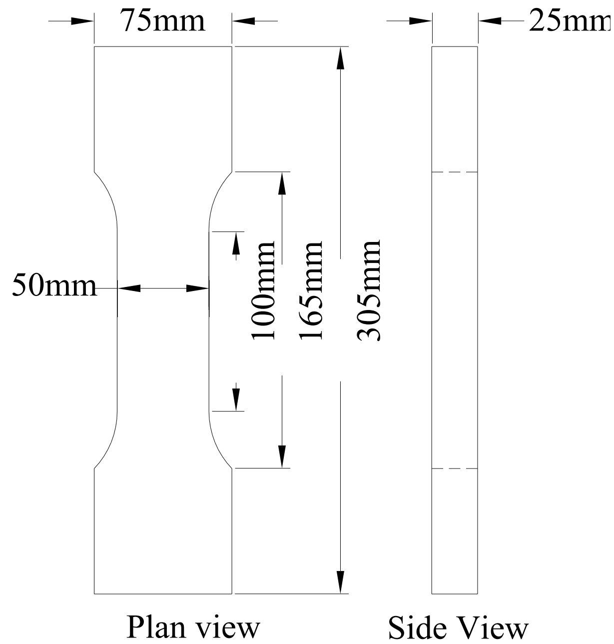

Figure 7 Dimensions of tensile specimen

3 EXPERIMENTAL TEST RESULTS AND COMPARISON TO SIMULATIONS

The proposed simulation model is applied to predict the stress-strain behavior of PVA-ECC specimens tested in uniaxial tension. The specimens have a dogbone shape (Figure 7) and are 305 mm long, 25 mm thick, and have a gauge length of 100 mm. Specimens of the shape shown in Figure 2 were made along with the dogbone specimens from the same mix to identify the σ_B–δ curves of this composite. Both the notched specimens and the dogbone specimens were tested under uniaxial load at the age of 28 days. The experimentally obtained σ_B -δ curves of the notched specimens are shown in Figure 4. The parameters that describe the envelop of the σ_B -δ curves are summarized in Table 2. This information is taken as input parameters of the simulation model and the predicted stress-strain curves for the dogbone specimens are compared with experimentally obtained stress-strain curves in the uniaxial tension test in Figure 8(a) and (b).

Table 2 Parameters of σ_B -δ envelope

Parameter Name	Value
σ_{fc}	3.2 – 4.8 MPa
σ_i	1.82 – 2.97 MPa
$\sigma_{B,peak}$	2.9 – 4.6 MPa
δ_0	0.17 - 0.22 mm
σ_1	1.0 MPa
δ_1	0.60 mm
δ_2	2.0 mm

Since a random σ_B -δ curve from within the experimentally obtained envelope is assigned to each potential crack location in each simulation run, the obtained results for the composite stress-strain curve differ as well in each simulation. Figure 8(a) shows three simulated results plotted in the same figure. The comparison shows that the simulation results agree well with experimental data. In addition, the plotted results demonstrate that the simulation program developed using aforementioned concept is capable of capturing the multiple cracking phenomenon and the strain hardening behavior of ECC under direct tensile loading.

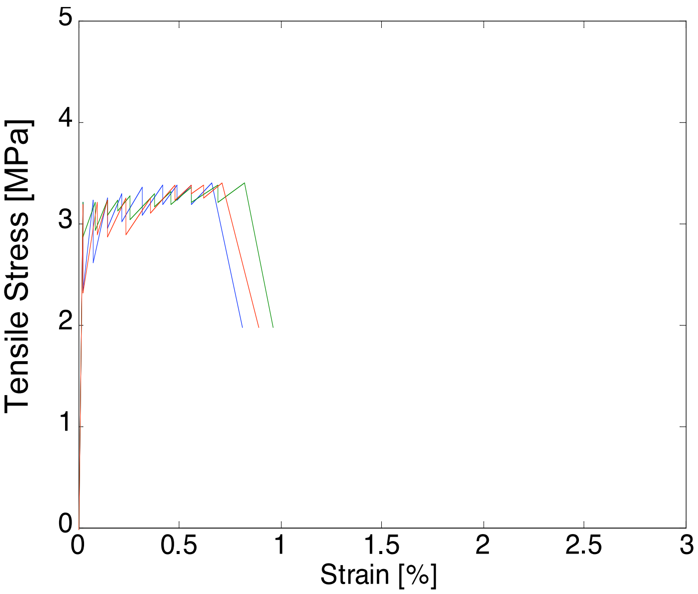

Figure 8a Simulated σ-ε curves

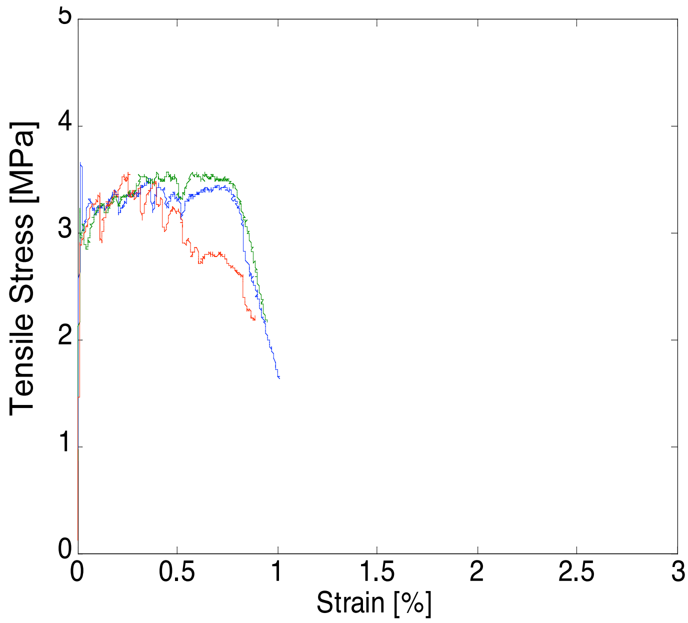

Figure 8b Experimentally obtained σ-ε curves

This simulation procedure can offer other related results such as evolution of crack spacing and a quantitative assessment of crack widths as a function of composite tensile strain (Figure 9a).

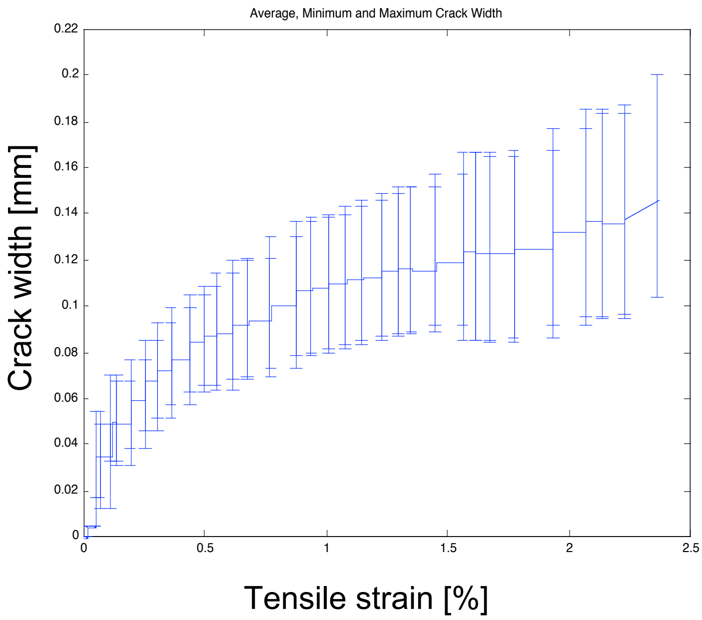

Figure 9a Range of crack widths obtained from simulation procedure

The predictions of crack widths as a function of composite tensile strain resulting from the simulation procedure have been compared to experimental data and showed close correlation (Figure 9b). The crack formation (Figure 10) of an ECC specimen under direct tensile loading was continuously monitored during the experiment using an image capturing and analysis system (ARAMIS). This system allows placement of virtual deformation gages after the test has been conducted and provides information on the deformations of the entire specimen surface and at particular user-defined locations.

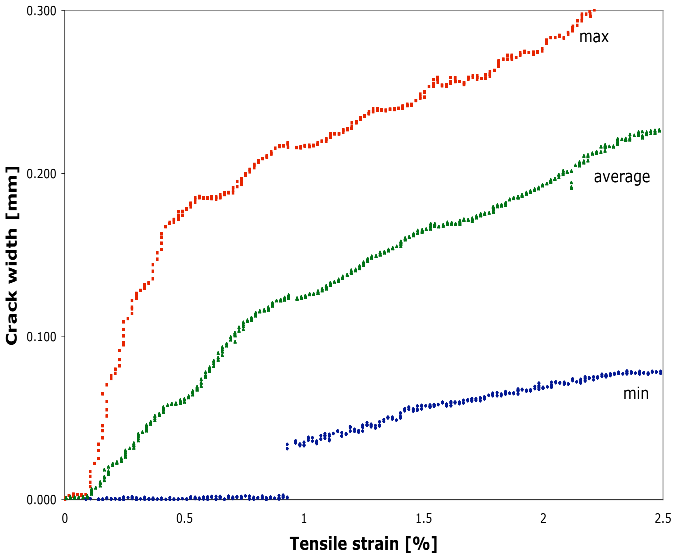

Figure 9b Range of crack widths obtained from experimental testing

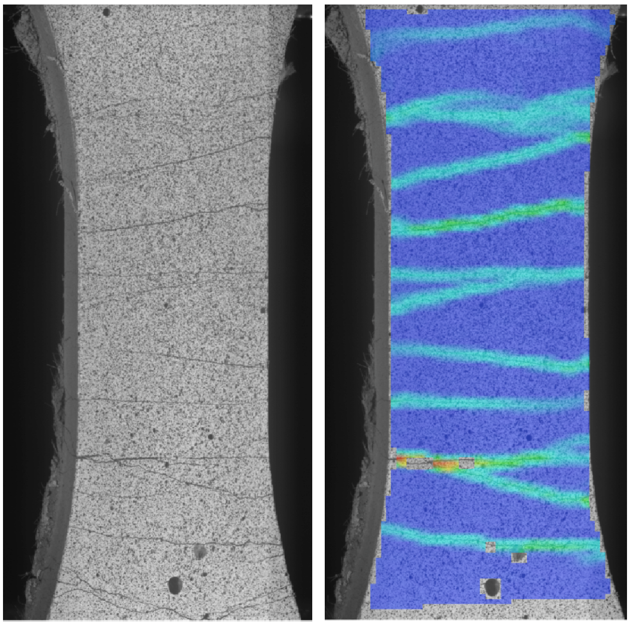

Figure 10 Cracking in ECC tensile specimen and visualization with ARAMIS

4 CONCLUSIONS

A method to simulate and predict the multiple cracking and strain hardening behavior of Strain Hardening Cementitious Composites (SHCC) under uniaxial tension was developed based on experimental information of the fiber bridging stress-crack opening relationship of the composite. Utilizing this information as input parameters of the simulation of the composite tensile stress-strain behavior, the variability of composite material properties, such as matrix flaw size, fiber tensile strength, fiber matrix interface characteristics, and fiber orientation, can be realistically incorporated. The multiple cracking and strain-hardening behavior can be captured by the suggested simulation model. In addition, the evolution of crack width and spacing can be quantified. The simulated response and experimentally obtained stress-strain behavior of SHCC are in agreement. The proposed method can serve as a tool in estimating the stress-strain behavior of SHCC based on σB -δ information, which is essential in the design of structural applications using SHCC. The simulation model can also be used to design SHCC materials with a target tensile stress-strain response and crack width limit by identifying the optimal range of matrix first cracking strength, peak fiber bridging strength and fiber bridging stiffness.

The image capturing and analysis system ARAMIS has been used to confirm the results of the simulation procedure and close correlation between model prediction and experimental results was found in this investigation.

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