Micromechanics-Based Design of Strain Hardening Cementitious Composites (SHCC)

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Abstract. This paper reviews the research and development of micromechanics-based design theory of strain hardening cementitious composites (SHCC) at different scale, linking the microstructure at micro scale with the composite tensile behavior at macro scale through fiber bridging properties at meso scale. Micromechanics relates macroscopic properties of SHCC to its microstructures, and forms the theoretical basis of SHCC design theory. So the single fiber pullout behavior at micro level lays the foundation of the scale-up research and has been investigated under various loading conditions. Based on the single fiber pullout behavior, analytic tools on micromechanics-based strain hardening model have been developed in closed or numerical forms. And it is widely applied as design guideline in guiding ingredients selection and component tailoring to achieve desired strain hardening performance. Afterwards, the micromechanics-based concept has been extended to develop models for tensile stress-strain properties and cracking process of SHCC. Therefore, the micromechanics-based design methodology of SHCC becomes holistic in the sense of obtaining the ultimate composite behavior with given micromechanical parameters, and versatile in various SHCC design, i.e. towards durability performance with charactering the crack pattern. It is expected that the micromechanics-based design tools capable of capturing the essence of SHCC behavior, should help structural designers take full advantage of SHCC material in infrastructure system design.

Keywords: Micromechanics · Strain hardening cementitious composites (SHCC) · Strain hardening model · Tensile stress-strain model

1 Introduction

Strain hardening cementitious composites (SHCC) is named after their ability to resist increased tensile force, with exhibiting multiple cracking and strain hardening beyond the point of first cracking as shown in Fig. 1. A large body of SHCC versions has been developed using local material ingredients in various countries, including USA (Li 2002, 2003), Japan (Japan Society of Civil Engineers 2008; Kunieda and Rokugo 2006), Europe (Mechtcherine 2013; Mechtcherine et al. 2012), and S. Africa (Boshoff and Van Zijl 2007a; Van Zijl et al. 2012).

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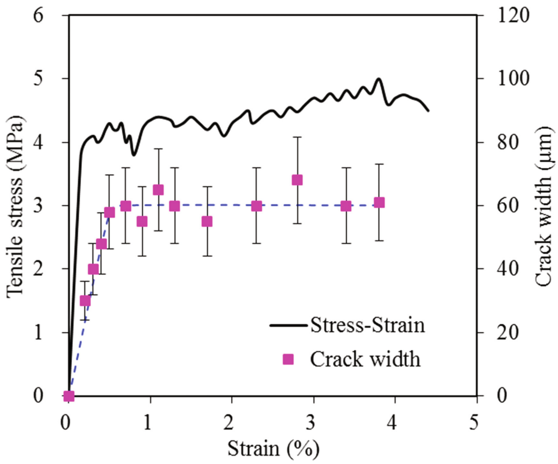

Fig. 1. Typical tensile stress-strain curve of SHCC (Yang et al. 2008).

The phenomenological modeling tensile behavior of SHCC have been developed with finite element method (FEM) (Boshoff and Van Zijl 2007b; Vorel and Boshoff 2012), lattice type models (Luković et al. 2014; Schlangen and Qian 2009), and micromechanics-based analytical method (Huang et al. 2016; Kabele 2003, 2007; Li and Leung 1992; Lin et al. 1999a). For finite element models of SHCC, many assumptions leads to less accuracy and cannot reflect inner physical mechanism. Although lattice type models enable insight into the influence of some parameters, it is still quite limited to discover the true mechanism. And these two types of models have been developed aiming to applying into the computational simulation of structures. To the point of SHCC material design, micromechanics-based design theory is the only specific method based on consideration of the mechanical interactions between fiber and matrix via an interface.

The principles of micromechanics was firstly introduced by Li (Li and Leung 1992) and gained significant development in the last decade of the 1990s (Kanda and Li 1998a, b; 1999a, b; Leung and Li 1989; Leung 1996; Li and Obla 1994, 1996; Li et al. 1993; Lin et al. 1999a; Lin and Li 1997; Maalej et al. 1995a). By then, a relative mature micromechanics-based strain hardening model of SHCC under monotonic loading was well developed for different types of fibers. In the following decade, the attention is mainly focused on the application of the micromechanics design theory in guiding SHCC component optimization, e.g. tailoring of fly ash content (Wang and Li 2007), fiber types (Yang and Li 2010), fiber/matrix interface (Li et al. 2002), and flaw size distribution (Wang and Li 2004). Further development also has been made for micromechanics-based strain hardening model under different loading conditions, mainly by Yang (Yang and Li 2014; Yang et al. 2008) and his group (Li and Yang 2017; Qiu and Yang 2016). In addition, the micromechanics-based design theory is also extended to modelling the multiple cracking behavior from the perspective of crack spacing (Kanda et al. 2000; Li et al. 2017; Lu and Leung 2016). By now, the micromechanics-based design methodology of SHCC becomes holistic in the sense of obtaining the ultimate composite behavior with given micromechanical parameters, and versatile in various SHCC design, i.e. towards durability performance with charactering the crack pattern.

Around the world, the concept of micromechanics deployed for SHCC development is increasingly recognized as a powerful tool to identify the dominant mechanisms in terms of fiber, matrix and fiber/matrix interface (Huang et al. 2016; Kabele 2007; Paul and Van Zijl 2013a, b). Kabele (2007) firstly proposed the semi-numerical multiscale modeling framework for SHCC based on the single fiber pullout model by Lin et al. (Lin et al. 1999a). Huang et al. (2016) improved Kabele model (Kabele 2007) by considering random fiber distribution. These semi-numerical models can simulate the tensile behavior of SHCC capable of capturing the physical mechanism, but it is on the premise of satisfying the strain hardening criteria.

In this paper, it only reviews the current state-of-the-art of the theoretical research and development in micromechanics-based design theory of SHCC at different scale, linking the microstructure at micro scale with the composite tensile behavior at macro scale through fiber bridging properties at meso scale. The concept of micromechanics deployed for SHCC design is emphasized, envisioned in future that SHCCs can be easily designed for specific requirements using micromechanics-based design theory.

2 Micromechanics-Based Design Methodology: Scale Linking

The philosophy behind the micromechanics-based design methodology of SHCC is scale linking as shown in Fig. 2, which links the microstructure at micro scale with the composite tensile behavior at macro scale. For individual fibers, the pullout behavior is largely governed by the fiber and interface properties, representing by single fiber pullout behavior. Integration of the bridging force contributed by fibers crossing the crack yields the fiber bridging stress σ versus crack opening δ relation, which describes the single-crack behavior. The propagation of cracks is influenced by the characteristics of the fiber bridging force. If steady state cracking occurs with a flat crack formed under constant ambient stress, and the cracking stress is also below the maximum bridging stress, then the composite has strain hardening potential. To form these multiple flat cracks, however, it is necessary to first initiate them from pre-existing flaw sites. The initiation of cracks is determined by the matrix cracking strength or critical flaw sizes. The evolution of multiple cracking does indeed reflect the spatial distribution of matrix cracking strength or flaws, until the bridging force capacity is exhausted. The modeling of micromechanisms at each material length scale and their linkages forms the theoretical framework of SHCC material design.

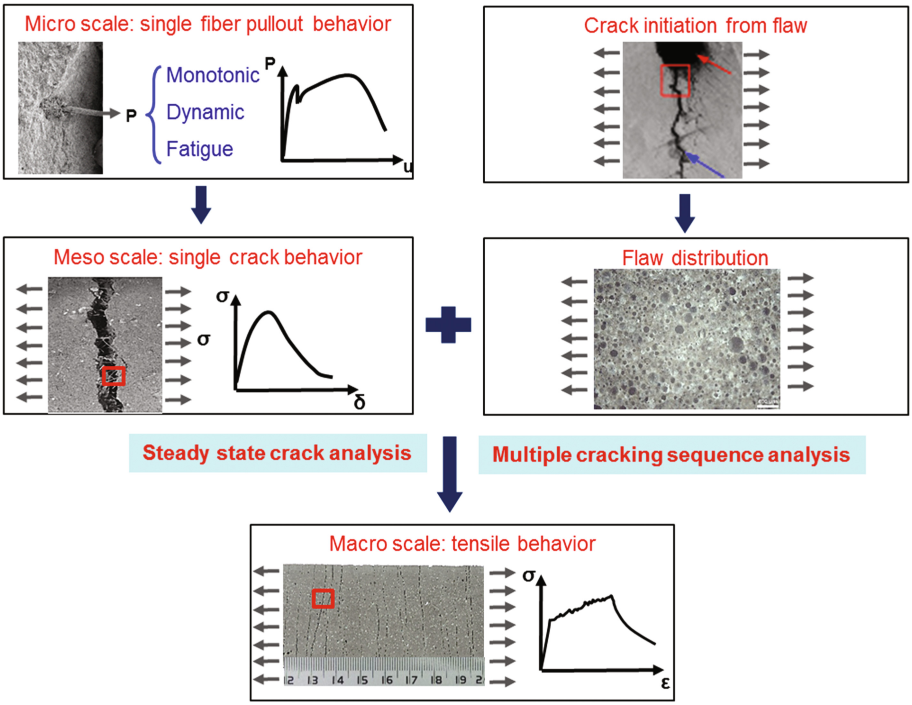

Fig. 2. Illustration of scale linking concept.

2.1 Steady State Crack Analysis

As above-mentioned, the tensile strain hardening behavior of SHCC is achieved by sequential development of matrix multiple cracking, for which two fundamental criteria are required to be met, that is, energy criterion and strength criterion represented by two inequalities as Eqs. (1) and (2) (Leung 1996; Li and Leung 1992; Yang et al. 2008). Equation (1) indicates that steady state crack propagation prevails under tension, namely, a flat crack can form through the matrix due to the bridging of fibers across the crack as Fig. 3. Equation (2) allows the bridging fibers to sustain the load and further loading initiates another micro-crack from another flaw. Repeated formation of such steady state cracks results in multiple cracking and strain hardening behavior as depicted in Fig. 1.

$$J'_b \geq J_{tip} \tag{1}$$

$$\sigma_0 \geq \sigma_c \tag{2}$$

where J'_b is the complementary energy, which can be calculated from the bridging stress σ_B versus crack opening δ curve, J_{tip} is the crack tip toughness, σ_0 is the maximum bridging strength, σ_c is the composite tensile cracking strength.

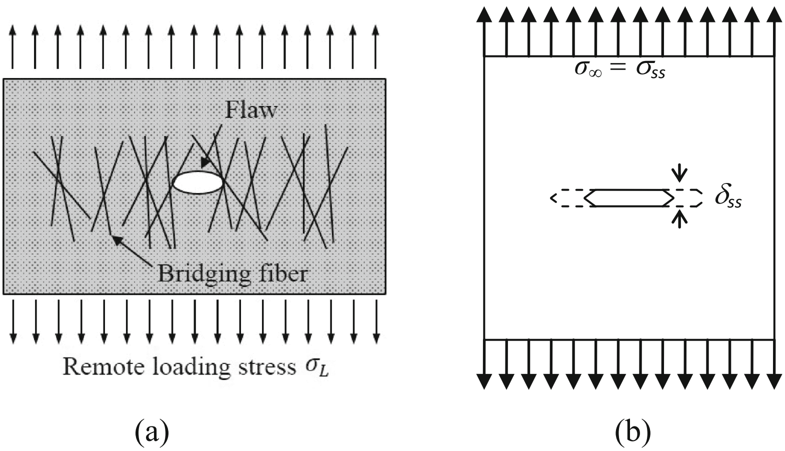

Fig. 3. Illustration of steady state crack mode (a) starting from initial flaw and (b) propagating at constant ambient load σ_{ss} and crack opening δ_{ss} (flat crack).

This steady state crack analysis is applicable in both static loading and dynamic loading, which has been proved by Yang and Li (2012, 2014). Through the analysis of the dynamic energy rate for a crack propagating at velocity V, the same result is derived as Eq. (1) for the static lading case with V = 0.

3 Micro-Scale: Single Fiber Pullout Behavior

3.1 Single Fiber Pullout Behavior

When a fiber is monotonically pulled out from the matrix, tunnel crack propagation along the fiber-matrix interface starts until the fiber is fully debonded from matrix followed by slippage of fiber out of the tunnel (Redon et al. 2001). The single fiber pullout behavior is generally classified into two categories, i.e., friction-dominant type like polyethylene (PE) fiber (Li and Leung 1992) and chemical bond-dominant type like polyvinyl alcohol (PVA) fiber (Lin et al. 1999a). Figure 4 shows the general profile of single fiber pullout curves for these two categories. As can be seen, there are three stages associated with the load-displacement curve for chemical bond-dominant type as Curve B. *Stage I*: initial elastic stretching of the fiber free length (the portion not embedded), followed by debonding. *Stage II*: the debonding stage continues until reaching the maximum load and a distinct load drop occurs. This load drop is an indication of chemical bond because it would not appear if the interface is frictionally bonded only. Physically, the load drop represents the transition from both chemical bond and friction bond controlled debonding stage to the pullout stage with friction bond only. *Stage III*: After complete debonding of the interface, chemical bond does not exist but frictional bond could effectively increase due to fibrillation of fiber surface sliding against surrounding matrix. For friction bond-dominant type as Curve A,

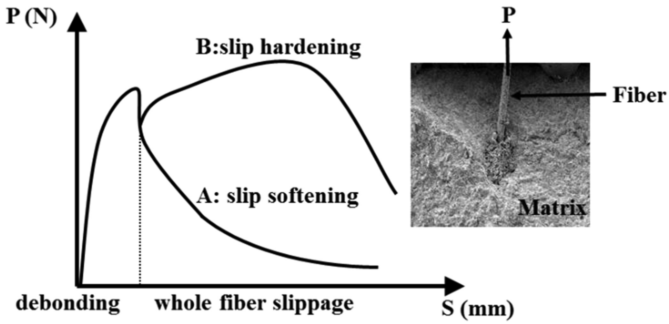

Fig. 4. General profile of single fiber pullout curves.

it includes two stages. Stage I is the same as that of Curve B. In Stage II, the fiber slips out with friction bond only, performing slip softening behavior.

The single fiber pullout behavior has been studied according to different interfacial properties, Li and Leung (1992) adopted a simple model for friction-dominant type like PE fiber. Considering a single fiber with an embedded length of L_e, the fiber pullout load P versus crack opening δ may be obtained from a shear-lag analysis as Eqs. (3) and (4).

Debonding stage:

$$P(\delta) = \sqrt{\frac{\pi^2(1+\eta)E_f d_f^3 \tau}{4}\delta} \quad (\delta \le \delta_0) \tag{3}$$

Slippage stage:

$$P(\delta) = \pi \tau d_f (L_e - \delta) \quad (l/2 \ge \delta > \delta_0) \tag{4}$$

$$\delta_0 = \frac{4l^2\tau}{(1+\eta)E_f d_f} \tag{5}$$

$$\eta = \frac{V_f E_f}{V_m E_m} \tag{6}$$

where δ_0 corresponds to the crack opening at which frictional debonding is completed, diameter d_f, elastic modulus E_f, and with an interfacial frictional bond strength τ, V_f, V_m are the fiber and matrix volume fractions respectively, and E_m is the elastic modulus of the matrix.

For chemical bond-dominant type like PVA fiber, Lin et al. (1999a) developed an analytical model for monotonic single fiber pullout load P versus crack opening δ, as explicitly expressed in Eqs. (7)–(9).

Debonding stage:

$$P(\delta) = \sqrt{\frac{\pi^2(1+\eta)E_f d_f^3 \tau_0}{2}\delta + \frac{\pi^2 E_f d_f^3 G_d}{2}} \quad (0 \le \delta \le \delta_0) \tag{7}$$

Slippage stage:

$$P(\delta) = \pi\tau_0 d_f \left(1 + \frac{\beta(\delta - \delta_0)}{d_f}\right)(L_e - \delta + \delta_0) \quad (\delta_0 \le \delta \le L_e) \tag{8}$$

$$\delta_0 = \frac{2\tau_0 L_e^2(1+\eta)}{E_f d_f} + \sqrt{\frac{8G_d L_e^2(1+\eta)}{E_f d_f}} \tag{9}$$

where L_e is the fiber embedment length into the matrix, G_d is the interface chemical bond, τ_0 is the initial frictional bond strength, and β is the slip-hardening coefficient.

3.2 High Loading Rate Single Fiber Pullout Behavior

Literatures on strain-rate effects of SHCC reported that the tensile strain capacity decreases while the tensile strength increases with increasing strain-rate (Douglas and Billington 2005; Mechtcherine et al. 2011a, b; Yang and Li 2012). It promotes the study of the microstructural sources responsible for rate dependence in SHCC by Yang and Li (2014). Experimental investigations were carried out to discover that the fiber stiffness E_f, the fiber strength σ_{fu}, and the chemical bond G_d are loading rate sensitive, the interfacial friction bond τ_0, the slip hardening coefficient β and the fiber strength reduction factor f' show negligible rate dependence over the tested loading rates. The strain-rate range was limited to between 10^{-5} and 10^{-1} s^{-1} which corresponds to quasi-static to low speed impact loading rates (Bischoff and Perry 1991), so further studies can be extended to higher strain effects and dynamic dependent micromechanical parameters may be expected to incorporated in to the single fiber pullout model.

3.3 Fatigue Dependent Single Fiber Pullout Behavior

In SHCC, fibers provide effective means to suppress the brittleness of cement-based materials. Under fatigue loading, fiber bridging of SHCC can effectively relieve the stress concentration at the crack tip, thus decelerating the crack propagation and extending the fatigue life of the structure (Lee and Barr 2004). While it was found that the fiber bridging quality deteriorates continuously with fatigue loading (Zhang et al. 2000). The nature of the fiber bridging deterioration originates from the fatigue-induced fiber and fiber/matrix interfacial deterioration, which has been experimentally characterized by Qiu et al. (2016). It was found that the in-situ strength of the fiber decreased with increasing fatigue cycles N, the chemical bond G_d was fatigue independent and the friction bond τ_0 increased with fatigue cycles N and fatigue loading levels P_{max}. To capture these phenomena, Qiu and Yang (Qiu and Yang 2016) proposed a new fatigue dependent single-fiber pullout model based on the analytical model of single fiber pullout behavior under monotonic loading by Lin et al. (1999b). The relation of the fiber pullout load P versus crack opening δ became a function related to fatigue cycles N and fatigue loading levels P_{max} by introducing the debonding crack length Δ_a induced by fatigue loads and changing the fatigue dependent friction bond τ.

Debonding stage:

$$P(\delta) = P(\delta, N_d, P_{\max}) \tag{10}$$

$$a = \min\{a_0 + \Delta a(N_d, P_{\max}), L_e\} \tag{11}$$

$$\tau = \tau_0[1 + \gamma_d(N_d, P_{\max})] \tag{12}$$

Slippage stage:

$$P(\delta) = P(\delta, N_s, P_{\max}) \tag{13}$$

$$\tau = \tau_0\left[1 + \beta(\delta - \delta_0)/d_f\right][1 + \gamma_d(N_d, P_{\max})][1 + \gamma_s(N_s, P_{\max})] \tag{14}$$

where N_d is the number of fatigue load cycles applied during the debonding stage, γ_d is the fatigue debonding hardening coefficient, N_s is the number of fatigue load cycles applied during the slippage stage, γ_s is the fatigue slippage hardening coefficient.

4 Meso-scale: Fiber Bridging Along Single Crack

On the meso-scale, the stress carried across a crack is a composite action of many fibers bridging across this crack as Fig. 5(a). It is cast in terms of $\sigma_B(\delta)$ curve as Fig. 5(b) (Yang et al. 2008), and can be obtained by averaging over the contributions of all bridging fibers based on the P-δ relation of a single fiber pullout (Lin et al. 1999a).

$$\sigma_B(\delta) = \frac{4V_f}{\pi d_f^2}\int_{\varphi=0}^{\pi/2}\int_{z=0}^{\left(\frac{L_f}{2}\right)cos\varphi} P(\delta)p(z)p(\varphi)dzd\varphi \tag{15}$$

where $p(\varphi)$ and $p(z)$ are the probability density functions of the orientation angle φ and the centroid distance of a fiber from the crack plane z, respectively. As can be seen from Eq. (8), the calculation formula is the same for any loading condition, the only difference is the resulting $\sigma_B(\delta)$ curve due to the various dynamic dependent or fatigue dependent microstructural properties.

Many efforts have been devoted to solve Eq. (8) with closed-form solution based on different interface properties and fiber failure modes. Li (1992) derived an analytical solution based on the assumption of purely frictional interface with a constant interfacial stress. Lin and Li (1997) advanced the solution by taking into account the slip-hardening interfacial properties. In those models, however, fiber rupture has not been accounted for. In fact, fibers may rupture at their debonding or pullout stage, provided that the fiber bridging exceeds the fiber strength (Li et al. 2001; Wang et al. 1991). The effect of fiber

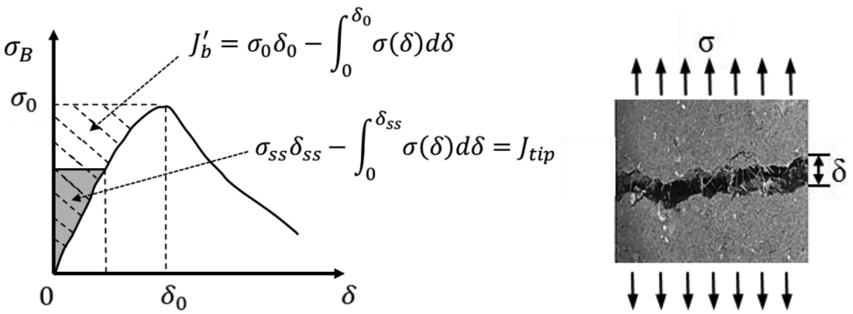

Fig. 5. (a) Illustration of single crack bridging by fibers; (b) typical $\sigma_B(\delta)$ curve of fiber bridging. *Hatched area* represents complimentary energy J_b'. *Shaded area* represents crack tip toughness J_{tip} (Yang et al. 2008).

rupture on crack bridging behavior was first investigated by Maalej et al. (1995b). Afterwards, Lin et al. (1999a) and Kanda et al. (1999a) extended the work of Maalej et al. (1995b) by introducing the interfacial chemical bond. But they only can consider the potential fiber rupture at the fiber debonding stage, and fiber pullout stage was considered to be one-way pullout at that moment. Accordingly and recently, Huang et al. (Huang et al. 2015) deducted a generic closed-form solution with consideration of the fiber rupture due to both chemical bond and slip hardening interfacial properties at both fiber debonding stage and fiber pullout stage, in which two-way fiber pullout was included.

It is noted that Yang et al. (2008) developed the solution in a numerical way with capturing the chemical bond and slip-hardening interfacial properties, as well as considering of all situations of the fiber rupture and two-way fiber pullout behavior. It is a more flexible and easy-to-use implementation of the fiber bridging model for further development of micromechanics-based design method of SHCC at macro-scale, than complex integration of closed-form solutions.

5 Macro-Scale: Multiple Cracking and Tensile Strain Hardening Behavior

5.1 The Variability of Macroscopic Composite Properties

The multiple cracking behavior is shown as strain hardening properties in the mechanical aspect, represented by tensile stress-strain (σ-ε) relation as shown in Fig. 1. And other multiple cracking characteristics involving crack opening, crack spacing, and crack number are reported to be of equal importance for durability performances (Ahmed and Mihashi 2007; Van Zijl et al. 2012). However, the multiple cracking behavior in particular tensile stress-strain curves and the crack pattern, has been observed to vary as shown in Fig. 6.

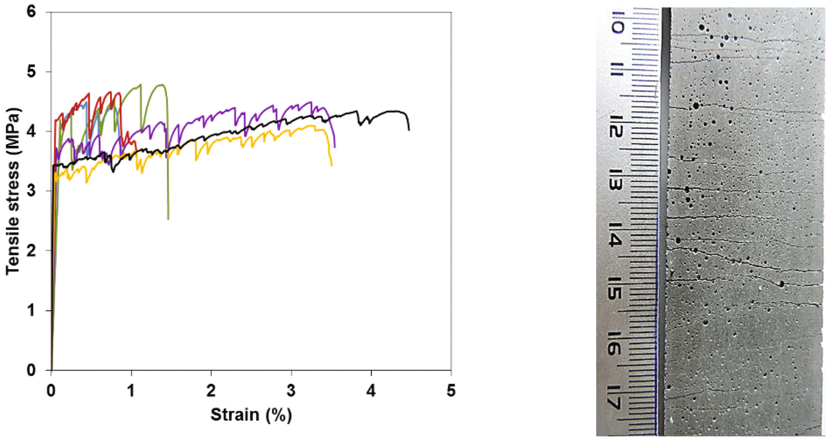

Fig. 6. The variability of $\sigma(\varepsilon)$ curves and crack patterns.

Kanda and Li (1998a, b) clarified the sequence and saturation of multiple cracking evolution based on PE-SHCC system, indicating that the premature failure mode (unsaturated multiple cracking), the crack spacing distribution and the crack opening distribution are attributed to the variations in initial matrix properties and fiber bridging properties. Li and Wang (2006) experimentally observed that the microstructure variability in particular fiber and flaw size distribution as shown in Figs. 7 and 8, significantly influences multiple cracking behavior in PVA-SHCC. The design of structures composed of SHCC should be based on the statistical consideration of the properties. The stochastic properties of most concern include the tensile stress-strain properties, the crack opening and the crack spacing.

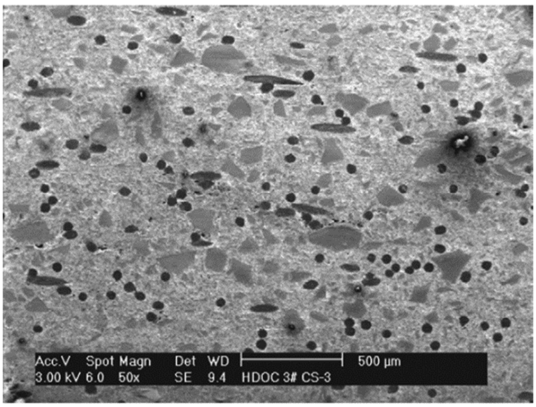

Fig. 7. SEM photo of an SHCC section (black dots are fibers) (Li and Wang 2006).

Fig. 8. Voids with various sizes in four SHCC sections sampled from a coupon specimen (Li and Wang 2006).

5.2 The Variability of Tensile Stress-Strain Properties

In order to consider the material variability, large margins of performance indices J'_b/J_{tip} and σ_0/σ_c were proposed (Kanda 1998; Kanda and Li 1998a, b), which is analogy to the build-in safety factor of the prescriptive-based design of structure. And it has been demonstrated experimentally that ECC reinforced with polyethylene (PE) fibers requires $J'_b/J_{tip} > 3$ and $\sigma_0/\sigma_c > 1.2$ to ensure saturated strain hardening behavior (Kanda and Li 1998a, b), while polyvinyl alcohol (PVA) fiber-reinforced ECC requires an even higher σ_0/σ_c of 1.45 and above (Kanda 1998). Nonetheless, this approach embeds the concept of material variability obscurely without considering the physical mechanism micromechanically and greatly dependent on empirical experiments.

5.3 The Variability of Crack Opening

The crack openings among multiple cracks have been observed to vary in the experiments (Kanda and Li 1998a, b; Van Zijl et al. 2016) due to the variation of fiber bridging properties, which has been reviewed as Sect. 4 in detail. To calculate the distribution of fiber bridging properties, the only need is to input varying values of micromechanical parameters into the closed-form solution or numerical solution of Eq. (8).

5.4 The Variability of Crack Spacing

The crack spacing of SHCC varies significantly due to the fiber and matrix randomness, flaw size distribution and fiber distribution in particular (Li and Wang 2006). In all existing theories, the transfer distance x_d is used as the ultimate crack spacing with full crack saturation. Theories for crack spacing calculation have been established in 1970s by Aveston et al. (Aveston and Kelly 1973; Aveston et al. 1974) for continuous aligned fiber reinforced brittle matrix composites, laying the foundation of subsequent research for random distributed fiber reinforced composites (Suwannakarn 2009; Wu and Li 1995). And the cracking strength of the composite is assumed to be uniform along the whole member, and all fibers are counted in with constant friction bond. Then, Lu and Leung (2016) derived the transfer distance x_d in terms of the crack opening in order to consider the variation of the composite cracking strength and fiber rupture contribution. Yet, it cannot consider the fiber rupture due to chemical bond and slip hardening properties, as well as the variation in interfacial properties.

5.5 Modeling Multiple Cracking Behavior

The micromechanics-based model for multiple cracking behavior is based on the concept of the crack spacing. Kanda et al. (2000) firstly proposed the stress-strain model based on theoretical calculation of ultimate crack spacing x_d. It derived a simple bilinear stress-strain curve without revealing the crack process, but it can predict the cases with unsaturated and saturated multiple cracking. Recently, Lu and Leung (2016) firstly developed a theoretical model for the cracking process and tensile stress-strain properties. In this model, the simulation of the cracking process is according to the cracking mechanism determined by the variation of composite cracking strength and the stress transfer distance $x_{d.}$ Once knowing the cracking process, the strain can be calculated by the number of cracks and the crack opening. Yet, this model assumed the same fiber bridging properties along the whole member and is specific to special case with saturated multiple cracking.

6 Conclusions

In previous application of this methodology, strain hardening criteria of SHCC has been widely recognized as the design guideline for achieving high strain capacity alone. With the development of the micromechanics-based design methodology, especially the consideration of the microstructure and composite variability, more and more attention on systematic design strategy for multiple cracking behavior of SHCC may be attracted with various design requirements. Currently, this micromechanics-based design methodology not only can be easily designed for required mechanical behavior of SHCC, but also can contribute to design towards durability performance which is related to the crack pattern. It is expected that the micromechanics-based design tools capable of capturing the essence of SHCC behavior, should help structural designers take full advantage of SHCC material in infrastructure system design.

More and more application cases of this SHCC design method are highly anticipated. As for the accuracy of the method, it is closely dependent on the correct distribution of the micromechanical parameters which requires further studies. Additionally, in terms of SHCC design, the component selections and proportions would be the direct question, which is also an open issue for all other design method of SHCC. So additional research is needed on the relation of the component selections and proportions with the micromechanical properties.

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