Micromechanics of Engineered Cementitious Composites (ECC): A critical review and new insights

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Abstract

ECC micromechanics relates material microstructures to the composite tensile behavior, which enables backward component tailoring to achieve targeted tensile performance at the minimum fiber dosage and forward prediction/modelling of ECC tensile behavior.

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This paper reviews the state-of-the-art ECC micromechanics, including its scale-linking approach, the mechanisms governing multiple cracking and tensile strain-hardening, and the detailed modelling and improvements at different length scales. Specifically, ECC micromechanics has been evolved from the deterministic-based approach to the stochastic-based model in order to take into account the heterogeneity of the microstructure for better simulation of the sequential formation of multiple steady-state cracking with various level of saturation. Furthermore, ECC micromechanics has been extended to different loading condition including dynamic loading and fatigue. Additional studies to further enhance the model have been discussed and proposed at the end of this review as well.

Keywords: *engineered cementitious composites (ECCs); micromechanics; fiber-bridging; steady-state cracking; strain-hardening; stochastic*

1 Introduction

Engineered cementitious composites (ECCs) or strain-hardening cementitious composites (SHCCs) is a type of high-performance fiber-reinforced cementitious composites (HPFRCCs), exhibiting tensile strain-hardening behavior of several percent with relatively low fiber dosage generally less than 2% by volume. With different locally available raw materials and performance requirements for different applications, many mix designs of ECCs have been developed and formulated in different countries, including the North America [1-11], Asia [12-20], Australia [21], Europe [22-25], the South America [26], and the South Africa [27, 28].

ECC tensile strain-hardening behavior is realized by tailoring the synergistic interaction between fiber, matrix, and fiber/matrix interface. ECC micromechanics has been developed to link material microstructures to composite tensile behavior. Once established, tensile properties of ECC such as tensile strength, tensile strain capacity, crack spacing, and crack width, can be assessed and modeled with a given set of micromechanical parameters (i.e., forward analysis). Alternatively, ECC micromechanics can be used to guide ingredients selection and components tailoring to achieve required composite tensile performance (i.e., backward tailoring). For example, ECC micromechanics has been applied to select suitable fiber type and dimension [29], to tailor matrix flaw size and distribution [30, 31], and to modify fiber/matrix interface [32] in order to achieve desired tensile strain capacity. ECC micromechanics has also contributed to impart special function and performance requirement, such as low density [33, 34], high early strength [35, 36], ultra-high strength [37, 38], self-healing [39-43], self-cleaning [44], and self-sensing [45-47].

Development and improvement of the ECC micromechanics continued for decades in different area including the fiber-bridging constitutive law, the pseudo strain-hardening criteria, and the ECC composite tensile behavior model [48-83]. Key milestones are summarized in Table 1 and are also described below. ECC micromechanics was firstly introduced by Li et al. in the early 1990s [69, 70], where the steady-state multiple cracking were revealed to depend on several micromechanical parameters. The closed-form analytical solutions of the fiber-bridging constitutive law was derived for ECC reinforced with short and randomly oriented hydrophobic fibers with friction-only fiber/matrix interface [53]. Later, hydrophilic fibers that are chemically bonded to the surrounding matrix [67] and exhibit slip-hardening behavior during fiber pullout [62] and lower apparent strength [63] were considered in formulation of the fiber-bridging constitutive law. Yang et al. [71] proposed a numerical solution to solve the fiber-bridging constitutive law, which allows practical extension of the model to incorporation new mechanisms such as two-way fiber pullout into consideration. Meanwhile, Huang et al. [83] developed an explicit closed-form solution of the fiber-bridging constitutive law for ECC reinforced with short and randomly oriented hydrophilic fibers.

Leung [59] established the theoretical ground of pseudo strain-hardening criteria, in which the maximum fiber-bridging strength must exceed the matrix cracking strength to ensure crack initiation at multiple locations, and the complimentary energy of the fiber-bridging must exceed the crack tip toughness to guarantee that steady-state cracking prevails. Subsequently, the pseudo strain-hardening criteria of ECC subject to dynamic loading [74] and fatigue [75] were developed. With the understanding of the heterogenous nature of ECC microstructures, empirical [76] and probabilistic-based pseudo strain-hardening criteria [77] of ECC were proposed.

Micromechanics-based ECC composite tensile behavior model was also developed. The sequential formation of multiple cracking was observed experimentally [78, 79]. Kabele and Stemberk [80] proposed an analytical model capturing the sequential formation of ECC multiple cracking considering matrix flaw size distribution. Lu and Leung [81] simulated the multiple cracking process in a closed-form solution based on the stress transfer theory. Li et al. [82] developed a stochastic-based model to capture the sequential formation of multiple cracking of ECC.

Table 1 Key milestones of the development of ECC micromechanics

Year	Milestone	Ref.
Fiber-bridging constitutive law		
1992	Complete closed-form solution was derived for hydrophobic fibers.	[53]
1998	Apparent fiber strength was considered for hydrophilic fibers.	[62]
1998	The slip-hardening interface was considered for hydrophilic fibers.	[63]
1999	The chemical bond was accounted for hydrophilic fibers.	[67]
2008	Analytically numerical solution was developed.	[71]
2015	Complete closed-form solution was derived for hydrophilic fibers.	[83]
Pseudo strain-hardening criteria		
1992	Pseudo strain-hardening criteria of ECC was firstly introduced.	[69]
1996	The exact condition of the pseudo strain-hardening criteria was derived.	[59]
2006	Practical pseudo strain-hardening criteria with two indices was proposed.	[76]
2014	Pseudo strain-hardening criteria of ECC under dynamic loading was derived.	[74]
2017	Pseudo strain-hardening criteria of ECC under fatigue loading was derived.	[75]
2018	Probabilistic-based pseudo strain-hardening criteria was developed.	[77]

ECC composite tensile behavior model		
1995	The cracking sequence was found experimentally.	[79]
1998	Multiple cracking mechanism was analyzed.	[78]
2005	An analytical model of multiple cracking process based on the matrix flaw size distribution.	[80]
2016	A model of the multiple cracking process was developed in a closed-form solution based on the stress transfer theory.	[81]
2019	A stochastic-based model of the multiple cracking process was developed with the consideration of microstructural variability.	[82]

In this paper, the state-of-the-art ECC micromechanics is reviewed. The concept and approach of ECC micromechanics at different scales are presented in the next section. The extensions of ECC micromechanics into dynamic loading and fatigue are illustrated in the third section. Finally, the main conclusions, limitations, and outlook are summarized in the last section.

2 ECC micromechanics

2.1 Scale-linking

The scale-linking approach represents the fundamental concept behind the development of ECC micromechanics. It was firstly shown and descried in detail by Li [72]. To date, this bottom-up scale-linking framework has been enriched with many researchers' contribution and become more holistic as shown in Fig. 1. In this approach, the ECC tensile strain-hardening behavior due to the sequential formation of multiple steady-state cracks in the composite macro-scale (mm-cm) is governed by the fiber-bridging properties and the matrix cracking properties in the meso-scale (μm-mm) via the pseudo strain-hardening criteria (e.g., steady-state crack analysis) and sequential multiple cracking analysis. The meso-scale properties can be further associated with material microstructure represented by a set of micromechanical parameters of fiber, matrix, and fiber/matrix interface in the micro-scale (nm-μm). These micromechanical parameters can be quantified experimentally via techniques such as single fiber pullout test and flaw size distribution characterization.

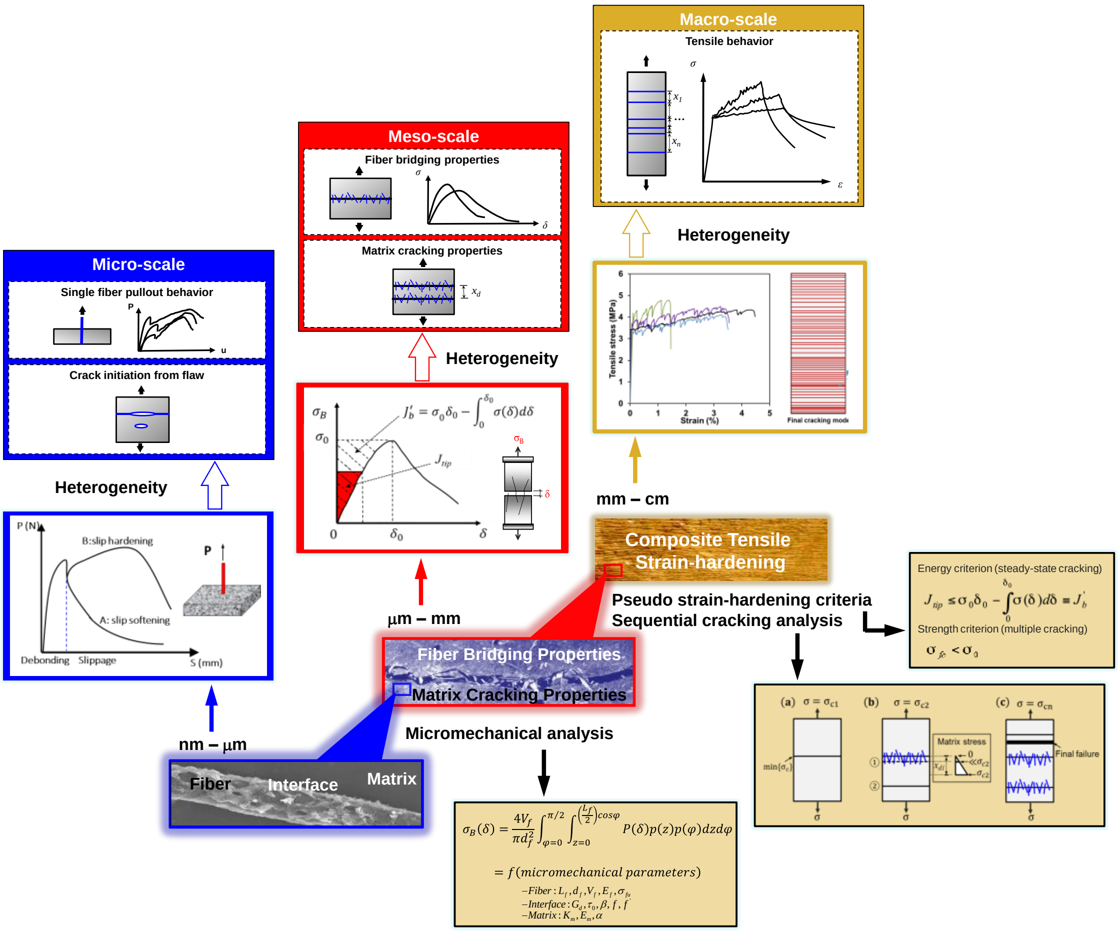

Figure 1 Illustration of scale-linking approach of ECC micromechanics

2.2 Micro-scale: Single fiber pullout behavior

Single fiber pullout behavior $P(\delta)$ in the micro-scale is modelled first. When a fiber is monotonically pulled out from the matrix, debonding between the fiber/matrix interface would occur first, which can be considered as a tunnel crack propagating along the interface. Upon full debonding, fiber slippage against the surrounding matrix would follow [84]. Depending on fiber types, two fiber slippage modes are typically observed as shown in Fig. 2. Curve B shows a slip-softening post-peak pullout behavior which is often associated with hydrophobic such as polyethylene (PE) fibers, while curve A demonstrates the slip-hardening post-peak pullout behavior which is unique for hydrophilic like polyvinyl alcohol (PVA) fibers.

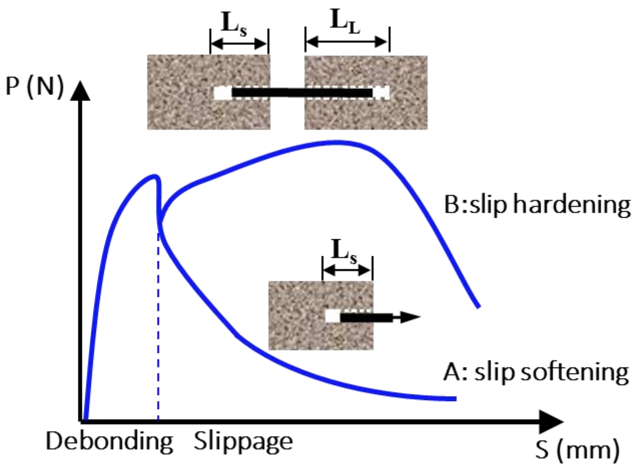

Figure 2 Illustration of single fiber pullout behavior

For hydrophobic such as polyethylene (PE) fiber systems [69], chemical adhesion between the fiber and the surrounding matrix is minimum and the fiber/matrix interface is mainly characterized by friction. Li and Leung [69] adopted a simplified model to describe the single fiber pullout behavior of the hydrophobic fiber. In this model, the fiber pullout load $P(\delta)$ can be obtained for a single fiber with an embedded length L_e based on a shear-lag analysis as shown in Eqns. 1 and 2.

Debonding stage: $$P(\delta) = \sqrt{\frac{\pi^2(1+\eta)E_f d_f^3 \tau}{4}\delta} \qquad (\delta \leq \delta_0) \tag{1}$$

Slippage stage: $$P(\delta) = \pi\tau d_f(L_e - \delta) \qquad (l/2 \geq \delta > \delta_0) \tag{2}$$

$$\delta_0 = \frac{4l^2\tau}{(1+\eta)E_f d_f} \tag{3}$$

$$\eta = \frac{V_f E_f}{V_m E_m} \tag{4}$$

where δ_0 corresponds to the crack opening when fiber is fully debonded from matrix, d_f is fiber diameter, E_f and E_m are elastic modulus of fiber and matrix, respectively, τ is fiber/matrix interfacial friction, and V_f and V_m are the total volume fractions of fiber and matrix, respectively. At the debonding stage, the pullout load increases with crack opening and reaches to the peak load when the fiber is fully debonded from the matrix. After the debonding process is completed, the fiber starts to slide out of the matrix. For interface with constant fraction, the pullout load would reduce with the slippage of the fiber because less fiber surface is in contact with the surrounding matrix to provide friction against fiber slippage.

For hydrophilic such as polyvinyl alcohol (PVA) fiber systems [67], strong chemical adhesion between the fiber and the surrounding matrix is often expected and the fiber/matrix interfacial bond strength is govern by both the chemical adhesion and friction. Lin et al. [67] developed an analytical model for monotonic single fiber pullout load $P(\delta)$ with fiber embedment length L_e and explicitly expressed in Eqns. 5 and 6.

$$\text{Debonding stage:} \quad P(\delta) = \sqrt{\frac{\pi^2(1+\eta)E_f d_f^3 \tau_0}{2}\delta + \frac{\pi^2 E_f d_f^3 G_d}{2}} \qquad (0 \le \delta \le \delta_0) \tag{5}$$

$$\text{Slippage stage:} \quad P(\delta) = \pi \tau_0 d_f \left(1 + \frac{\beta(\delta - \delta_0)}{d_f}\right)(L_e - \delta + \delta_0) \qquad (\delta_0 \le \delta \le L_e) \tag{6}$$

$$\delta_0 = \frac{2\tau_0 L_e^2(1+\eta)}{E_f d_f} + + \sqrt{\frac{8G_d L_e^2(1+\eta)}{E_f d_f}} \tag{7}$$

where G_d, τ_0, and β are the chemical bond strength, the friction, and the slip-hardening coefficient of the fiber/matrix interface, respectively. At the debonding stage, the pullout load increases with crack opening. Upon completion of debonding, a sudden load drop is observed. This is attributed to the complete loss of chemical adhesion between fiber and matrix and indicates the fiber pullout has entered into the friction-dominant slippage stage. Slip-hardening due to the jamming effect of fiber/matrix interface (i.e., accumulation of fiber debris in the interface tunnel due to fibrillation of fiber surface from slippage) can be modelled mathematically by means of the slip-hardening coefficient.

2.3 Meso-scale: Fiber-bridging constitutive law

The fiber-bridging constitutive law in the meso-scale governs the mode of crack propagation and the pseudo strain-hardening potential of ECC. It also largely determines the tensile strength and crack width of ECC. To model the fiber-bridging $\sigma_B(\delta)$ relation, the stress carried by multiple randomly oriented discontinuous fibers bridging across a crack is calculated as a function of crack opening as shown in Fig. 3 [71]. The $\sigma_B(\delta)$ relation (Fig. 3b) can be obtained by summing up the forces induced by each bridging fiber across the matrix crack per unit area considering the mechanics of single aligned fiber pullout, the mechanics of single inclined fiber pullout, and the random distribution of fibers in location and orientation [67].

$$\sigma_B(\delta) = \frac{4V_f}{\pi d_f^2} \int_{\varphi=0}^{\pi/2} \int_{z=0}^{\left(\frac{L_f}{2}\right)\cos\varphi} P(\delta, L_e, \varphi) p(z) p(\varphi) dz d\varphi \quad (8)$$

where φ is the fiber inclination angle, z is the centroid distance of a fiber from the crack plane, and $p(\varphi)$ and $p(z)$ are the probability density functions (PDF) of φ and z, respectively.

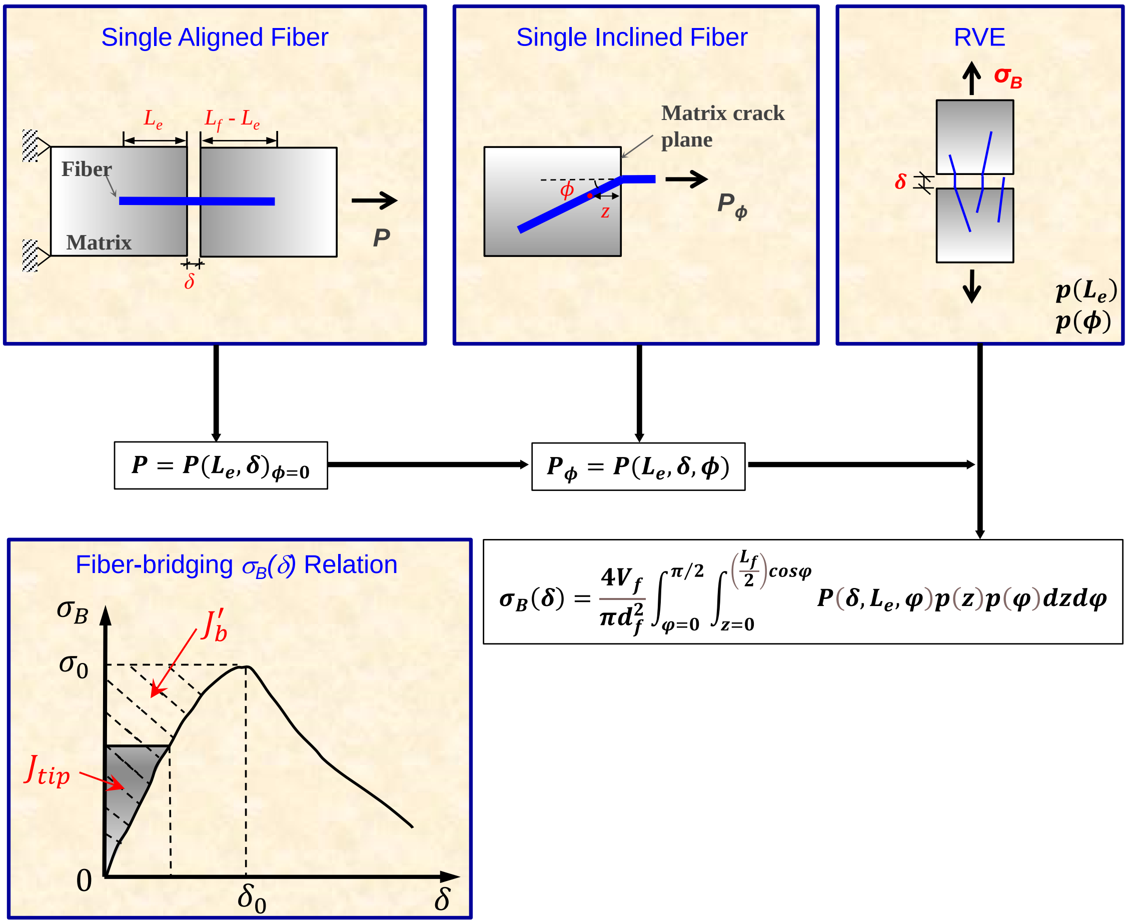

Figure 3 Modular construction of the fiber-bridging $\sigma_B(\delta)$ relation (Hatched area represents complimentary energy J_b'. Shaded area represents crack tip toughness J_{tip}).

Li [53] derived an analytical solution of Eqn. 8 for fiber/matrix interface with constant friction. Lin and Li [62] improved the solution by taking account of the slip-hardening fiber/matrix interface. Due to the complexity of the closed-form solutions, these analytical analyses did not take fiber rupture into consideration [51, 85]. Maalej et al. [58] reported potential fiber rupture in ECC and analyzed its effects on fiber-bridging behavior. Based on this observation, Lin et al. [67] and Kanda et al. [66] refined the analytical solution of fiber-bridging by taking fiber rupture into consideration.

Alternatively, Yang et al. [71] developed a numerical approach to solve Eqn. 8. Additional mechanisms including two-way fiber debonding and pullout, matrix micro-spalling, and Cook-Gordon effects were also considered in calculating the fiber-bridging $\sigma_B(\delta)$ relation. More recently, Huang et al. [83] proposed a closed-form solution for Eqn. 8 considering two-way fiber pullout and rupture at both the debonding stage and the slippage stage of the slip-hardening interface.

2.4 Steady-state crack analysis and pseudo strain-hardening criteria

The tensile strain-hardening behavior of ECC is attributed to the formation of multiple steady-state cracks, i.e., flat cracks form after initiating from defect sites and extend through the matrix under constant ambient load (Fig. 4b). This is different from the typical (modified) Griffith crack (Fig. 4a) in normal fiber-reinforced concrete (FRC), in which extension of crack tips results in widening of crack mouth. Continuous crack mouth widening leads to complete fiber pulled out and loss of bridging fibers across the crack, and thus reducing load carrying capacity.

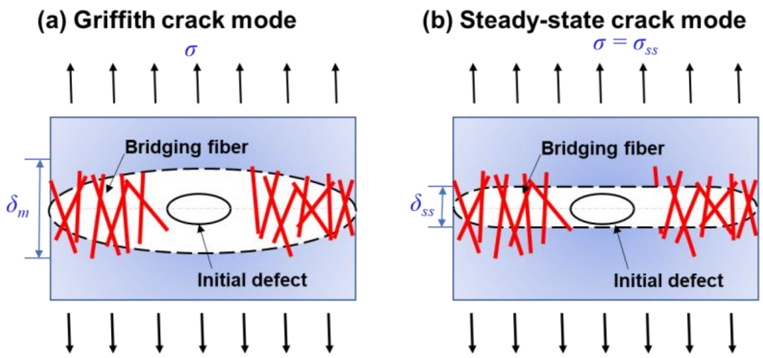

Figure 4 Illustration of (a) (modified) Griffith crack mode and (b) steady-state crack mode

The condition of stead-state cracking in a brittle matrix composite reinforced with aligned continuous fibers was first derived by Marshall and Cox [86] via the J-integral method. Later, Li and Leung [69] extended the analysis to a brittle matrix composite reinforced with randomly oriented discontinuous fibers.

$$\sigma_{ss}\delta_{ss} - \int_0^{\delta_{ss}} \sigma_B(\delta)d\delta = J_{tip} \quad (9)$$

where σ_{ss} is the steady-state cracking stress, δ_{ss} is the corresponding flat crack opening at σ_{ss}, $\sigma_B(\delta)$ is the fiber-bridging constitutive law, and J_{tip} is the crack tip toughness as shown in Fig. 3b. The left-hand side of Eqn. 9 represents the complementary energy of fiber-bridging, which can be considered as the energy input by external work minus the energy stored in the fiber-bridging. Therefore, the physical interpretation of the condition for steady-state cracking is the net available energy in the system must be sufficient to overcome the crack tip toughness for infinite crack extension at a constant ambient load. Yang and Li [87] numerically verified the condition for steady-state cracking and digitally visualized such steady-state crack propagation.

Another important condition for the formation of multiple steady-state cracks in ECC is that the fiber-bridging strength σ_0 must be greater than the composite tensile cracking strength σ_c. While the energy-based steady-state cracking criterion determines the mode of crack propagation, the strength-based crack initiation criterion ensures cracks can initiate from multiple defect sites. Overall, the pseudo strain-hardening criteria of ECC can be written in the following form [29, 65, 71, 78].

$$J_b' \geq J_{tip} \quad (10)$$

$$\sigma_0 \geq \sigma_c \quad (11)$$

As can be seen, the above analysis is deterministic and, in the ideal situation, satisfaction of both criteria should result in the formation of steady-state cracks at multiple sites simultaneously. In reality; however, multiple cracking in ECC always forms in sequential and the first crack is not necessary the final failure crack as observed in experiments [78, 82]. This led to the consideration of microstructure heterogeneity, originated from raw materials (e.g., variation of fiber diameter), processing (e.g., flaw size and distribution, non-uniform fiber distribution [88]), and curing, in the analysis.

Li and Wang [88] experimentally observed the variability of fiber and flaw size distribution as shown in Fig. 5, which significantly influences the saturation of multiple cracking and tensile strain-hardening capacity of ECC reinforced with PVA fibers (PVA-ECC). To take such variability into consideration of ECC design, large margins of pseudo strain-hardening (PSH) indices J_b'/J_{tip} and σ_0/σ_c were proposed to ensure that ECC multiple cracking prevails, and tensile strain-hardening can occur [76, 89, 90]. It has been experimentally demonstrated that $J_b'/J_{tip} > 3$ and $\sigma_0/\sigma_c > 1.2$ are necessary for a specific version of ECC reinforced with PE fibers (PE-ECC) [78] while an even higher σ_0/σ_c of 1.45 is needed for a certain PVA-ECC mix [89] to achieve saturated multiple cracking and strong tensile strain-hardening behavior. This approach is analogous to the factor of safety in structure design. The required margin (i.e., factor of safety) for a specific ECC mix; however, needs to be determined experimentally.

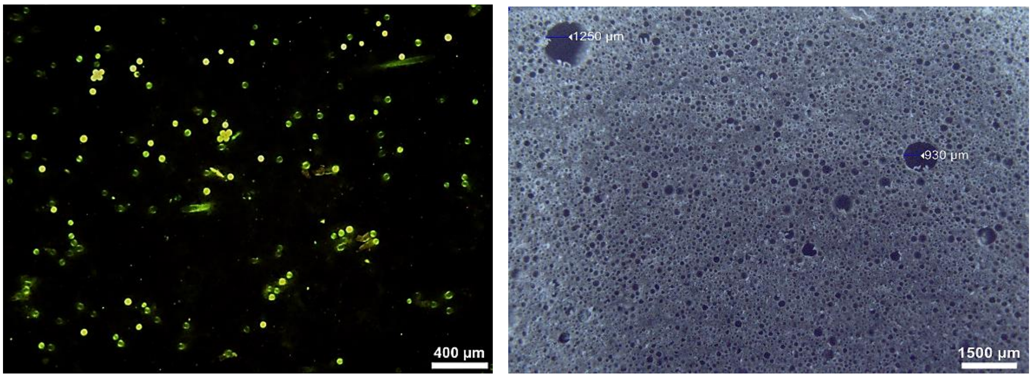

Figure 5 Photos showing the variability of (a) fiber distribution (yellow dots are fibers); and (b) flaw distribution in an ECC section

Li and Yang [77] proposed a probabilistic-based approach to explicitly account for the variation of raw materials and microstructure by considering all micromechanical parameters as random variables. As a result, the tensile strain-hardening criteria can be used for the establishment of two limit state surfaces (performance functions [77]).

$$G(x) = J_b' - J_{tip} = 0 \quad (12)$$

$$F(x) = \sigma_0 - \sigma_c = 0 \quad (13)$$

where x denotes each micromechanical parameter as random variable. $G(x) > 0$ and $F(x) > 0$ denote the 'safe' (i.e., tensile strain-hardening) domain, while $G(x) < 0$ and $F(x) < 0$ denote the 'failure' (i.e., tensile strain-softening) domain as shown in Fig. 6. The tensile strain-hardening potential is evaluated via the concept of probability of failure P_f, which can be determined by integrating the probability density function (PDF) over the failure domain (i.e., volume *abcd* in Fig. 6) once the probabilistic distribution of micromechanical parameters are determined [77].

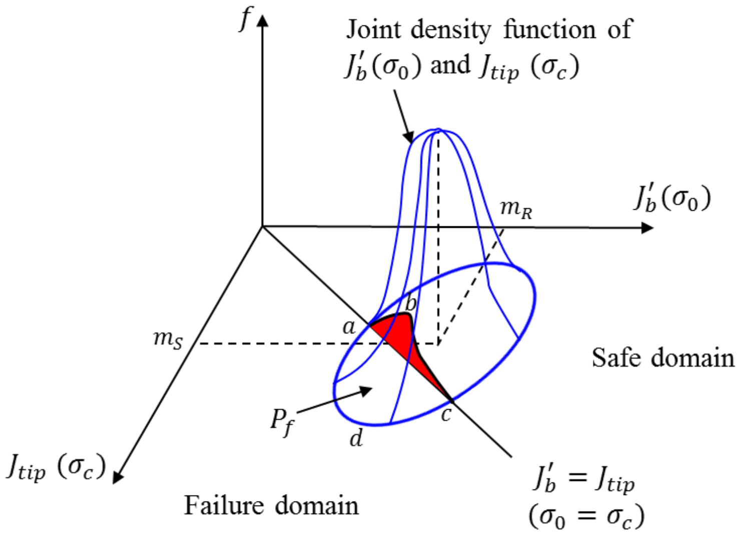

Figure 6 The probabilistic-based strain hardening evaluation method of ECCs with probability density function of indices [77]

2.5 Sequential multiple cracking analysis and critical stress transfer distance

Due to the heterogenous nature of ECC microstructure, the occurrence of multiple cracking is always in sequence and terminates at a random crack plane [77, 78]. The mechanism of multiple cracking sequence has been studied in [91]. Considering an ECC specimen with *n* divided sections, the first crack shall initiate at the section with the lowest composite cracking strength, i.e., min [σ_c], as shown in Fig. 7a. Satisfaction of both Eqns. 10 and 11 at this crack plane is the prerequisite condition to avoid damage localization. With continuous increase of externally applied stress, the next crack would occur at the location outside the critical transfer distance x_d of the existing crack (Fig. 7b). Continuation of the above process leads to the sequential formation of steady-state cracks from different crack planes as shown in Fig. 7b. When the satisfaction of both Eqns. 10 and 11 at the newly generate crack plane is not valid or the applied stress reaches the lowest fiber-bridging strength among all formed crack planes, i.e., min [σ_0], it defines the termination of multiple cracking and the final failure of the composites as shown in Fig. 7c.

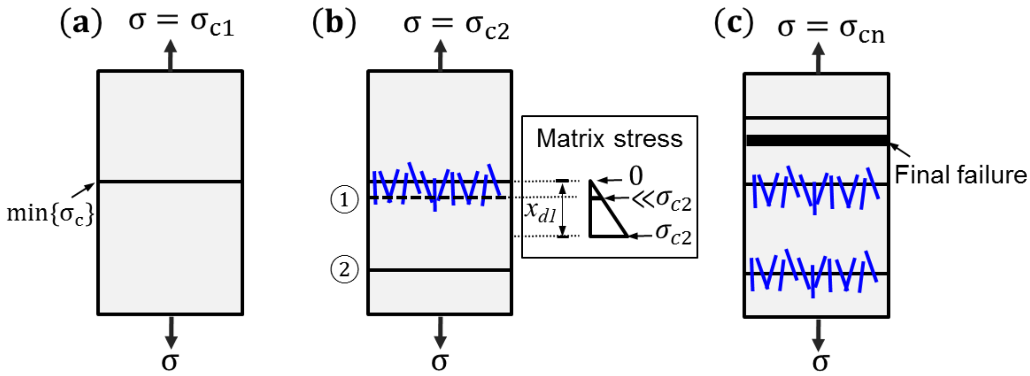

Figure 7 Illustration of sequential multiple cracking process [92]

The critical transfer distance x_d is the minimal distance necessary for the fiber-bridging stress transferring back to the matrix. The analytical solution of x_d calculation was proposed by Aveston et al. [93, 94] for the aligned continuous fiber-reinforced brittle matrix composite. Subsequent studies on x_d for the short and randomly oriented fiber-reinforced brittle matrix composite have also been carried out [79, 81, 95, 96] by considering force balance of the matrix between two crack planes by Eqn. 14 and as shown in Fig. 8 [96].

$$\sum[\pi d_f \tau(\delta) x_d] + \sum[P(\delta, L_e, \varphi) e^{f\varphi} - P(\delta, L_e, \varphi) \cos \phi] = \sum \sigma_{mu} \Delta V \qquad (14)$$

where $P(\delta, L_e, \varphi)$ is the fiber pullout force, φ is the fiber inclination angle [49, 97], and $\tau(\delta)$ is the fiber/matrix interface friction [84]. It is worth noting that the value of x_d for different crack plane varies because x_d is largely governed by the fiber-bridging $\sigma_B(\delta)$ relation of individual crack plane, which can vary from one crack plane to another due to ingredients variability and microstructure heterogeneity.

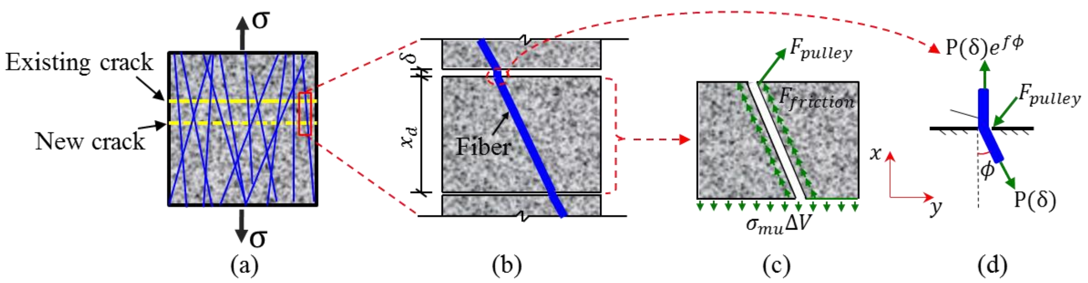

Figure 8 (a) An ECC sample under tension, (b) a representative volume element with single fiber, and free-body diagrams of (c) the matrix and (d) the bridging fiber in equilibrium [96]

2.6 Macro-scale: Composite tensile behavior

At the macro-scale, the ECC tensile behavior can be modelled by calculating its first cracking strength σ_{fc}, ultimate tensile strength σ_{mu}, tensile strain capacity ε, crack width δ, and crack spacing x. The strain capacity ε can be deduced using Eqn. 15.

$$\varepsilon = \frac{\sum_{i=1}^{n} \delta_i}{L} \quad (15)$$

where δ_i is the crack width, n is the total crack number, and L is the gauge length. Assuming the ECC specimen has uniform matrix strength and can achieve saturated multiple cracking, the strain capacity can then be calculated using Eqn. 16 for simplicity [1, 81, 93, 95, 98-103].

$$\varepsilon = \frac{\delta}{x} \quad (16)$$

where x is between x_d and $2x_d$, and x_d is the critical stress transfer distance. Kimber et al. [98] derived the theoretical average crack spacing of a aligned continuous fiber-reinforced brittle matrix composite and reported an average crack spacing of $1.337x_d$, where δ and x are deterministic values based on the assumptions. Kanda et al. [104] proposed a simple approach to modify crack spacing x with the consideration of flaw size distribution.

From the experimental observation of ECC cracking sequence, Lu and Leung [81] simulated the multiple cracking process based on the critical stress transfer distance x_d. The tensile stress-strain relation can be obtained as a closed form solution with deterministic δ and variable x_d, and the strain capacity can be calculated using Eqn. 15 consequently. Li et al. [105] further developed a multivariate model to capture the multiple cracking process with variable δ and x_d, outputting stochastic tensile stress-strain curves with stochastic crack characteristics including cracking sequence, and crack spacing and crack width distributions.

3 ECC micromechanics extension

3.1 Dynamic loading

The stress intensity at the tip of a running crack is different from the static case due to the inclusion of time-dependent terms. The energy release rate for a running crack with a propagation speed of V is defined as [106]

$$G(\Gamma) = \lim_{\Gamma=0} \int_{\Gamma} \left(W + \frac{1}{2}\rho V^2 \frac{\partial u_i}{\partial x}\frac{\partial u_i}{\partial x} \right) dy - \sigma_{ij}\, n_j \frac{\partial u_i}{\partial x} ds \qquad (17)$$

where W is the strain energy density, ρ is the material density in the initial state, u_i is the displacement, V is the crack propagation speed, σ_{ij} is the stress, and n_i is the unit normal vector. It is a path-independent J-integral in the present steady-state cracking problem of ECC [107]. Therefore, J_{tip} may be evaluated by the dynamic energy release rate with a close contour path around the crack tip as shown in Fig. 9, in which the applied tensile stress and crack opening are σ_{ss} and δ_{ss}, respectively [108]. The calculated result of J-integral expression for the dynamic case (i.e. $V > 0$) is the same as that for the static case (i.e. $V = 0$) as shown in Eqn. 10 [86]. Therefore, the steady-state crack analysis and the pseudo strain-hardening criteria as discussed in the Section 2.4 remain applicable for the dynamic loading condition [109].

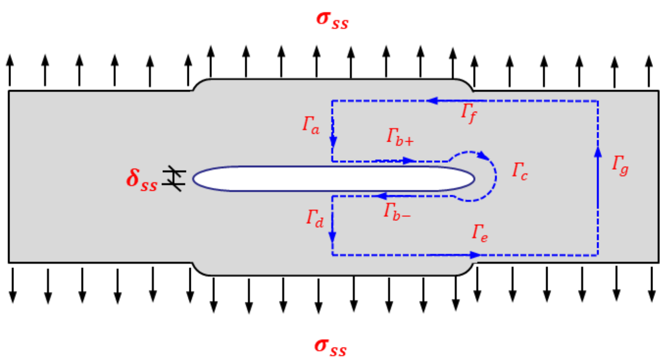

Figure 9 A contour path for dynamic energy release rate calculation

However, the micromechanical parameters are rate sensitive, and as the result the single fiber pullout behavior, the fiber-bridging $\sigma_B(\delta)$ curve, the pseudo strain-hardening indices, as well as the composite tensile behavior all become rate dependent. Experimental investigations at the micro-scale discovered that fiber modulus E_f, the matrix toughness J_{tip}, and the fiber/matrix interfacial chemical bond G_d exhibiting strong rate sensitivity; all increases with increasing loading rates [74]. This can lead to more fiber rupture as shown in [110]. As a result, the tensile strength increases while the tensile strain capacity decreases with increasing strain rates [109, 111, 112].

3.2 Fatigue

Similar approach as discussed in Section 3.1 has been adopted for determining the tensile strain-hardening performance of ECC under fatigue. While the same steady-state crack analysis and the pseudo strain-hardening criteria remain applicable, the micromechanical parameters are now fatigue dependent. As a result, the single fiber pullout behavior, the fiber-bridging $\sigma_B(\delta)$ curve, the pseudo strain-hardening indices, as well as the composite tensile behavior under fatigue behave very differently than those under static loading [113-116].

Qiu et al. [117] conducted the single fiber pullout test under fatigue and discovered a new fiber debonding mechanism. Furthermore, it also found that fiber/matrix interfacial friction and in-situ fiber strength are also fatigue sensitive. The debonding crack length Δa induced by fatigue was introduced and the fatigue dependent fiber/matrix interfacial friction τ was also included in the modelling of the single fiber pullout behavior during the debonding and the slippage stages under fatigue.

Debonding stage:

$$P(\delta) = P(\delta, N_d, P_{max}) \tag{18}$$

$$a = \min\{a_0 + \Delta a(N_d, P_{max}), L_e\} \tag{19}$$

$$\tau = \tau_0[1 + \gamma_d(N_d, P_{max})] \tag{20}$$

Slippage stage:

$$P(\delta) = P(\delta, N_s, P_{max}) \tag{21}$$

$$\tau = \tau_0\left[1 + \beta(\delta - \delta_0)/d_f\right]\ [1 + \gamma_d(N_d, P_{max})]\ [1 + \gamma_s(N_s, P_{max})] \tag{22}$$

where N_d and N_s are loading cycles in the debonding and the slippage stages, respectively, and γ_d and γ_s are the debonding-hardening coefficient and the slippage-hardening coefficient due to fatigue, respectively.

The new set of equations forms the basis for the formation of the fatigue dependent fiber-bridging $\sigma_B(\delta)$ curve [118]. By considering the fatigue sensitivity of micromechanical parameters, it was found the fiber-bridging effectiveness reduces under fatigue [114-116]. As a result, ECC under fatigue shows reduced saturation of multiple cracking and lower tensile strain capacity.

4 Conclusions and outlook

ECC micromechanics relates material microstructures represented by a set of micromechanical parameters in the micro-scale to the composite tensile behavior in terms of tensile stress-strain relation and crack characteristics in the macro-scale via the scale-linking approach. ECC micromechanics can be used as a tool for composite performance prediction (i.e., forward analysis) or to guide microstructure modification through component engineering and ingredients selection to achieve the optimum performance in terms cost and benefit (i.e., backward tailoring). Over the past few decades, ECC micromechanics has been improved by discovering and including comprehensive mechanisms to better capture the mechanical behavior of ECC at different length scales. It has been evolved from the deterministic-based model to the stochastic-based one in order to take into account the heterogeneity of the microstructure and to understand and simulate the sequential formation of multiple steady-state cracking with various level of saturation. Furthermore, ECC micromechanics has been extended to different loading condition including dynamic loading and fatigue.

Continue research is necessary to further enhance the model. Firstly, the composite tensile behavior is linked to a set of micromechanical parameters, such as fiber/matrix interfacial friction, which is not directly associated with mix composition, e.g., water-to-cement ratio, and is not straight forward to engineers. It would be a breakthrough if the micromechanical parameters can be further related to the mix composition in the nano-scale via cement chemistry. If successful, the model will be able to associate the composite tensile behavior to the mix composition directly, and this could lead to the development of a direct method for proportioning ECC mixes. Secondly, the current model assumes no interaction between individual cracks. In reality, cracks could branch and connect to the adjacent cracks [119]. It would be necessary to consider crack interaction in ECC micromechanics. This aspect would be particularly valuable and important when the ECC micromechanics-based model further extends to structural element scale for structural analysis where complex and combined loading in ECC structural element is anticipated. Thirdly, when considering the heterogeneity of ECC, all micromechanical parameters are taken as random variables. To better model the ECC bahavior, it is needed to know the probability density function (PDF) of each micromechanical parameter via experiments.

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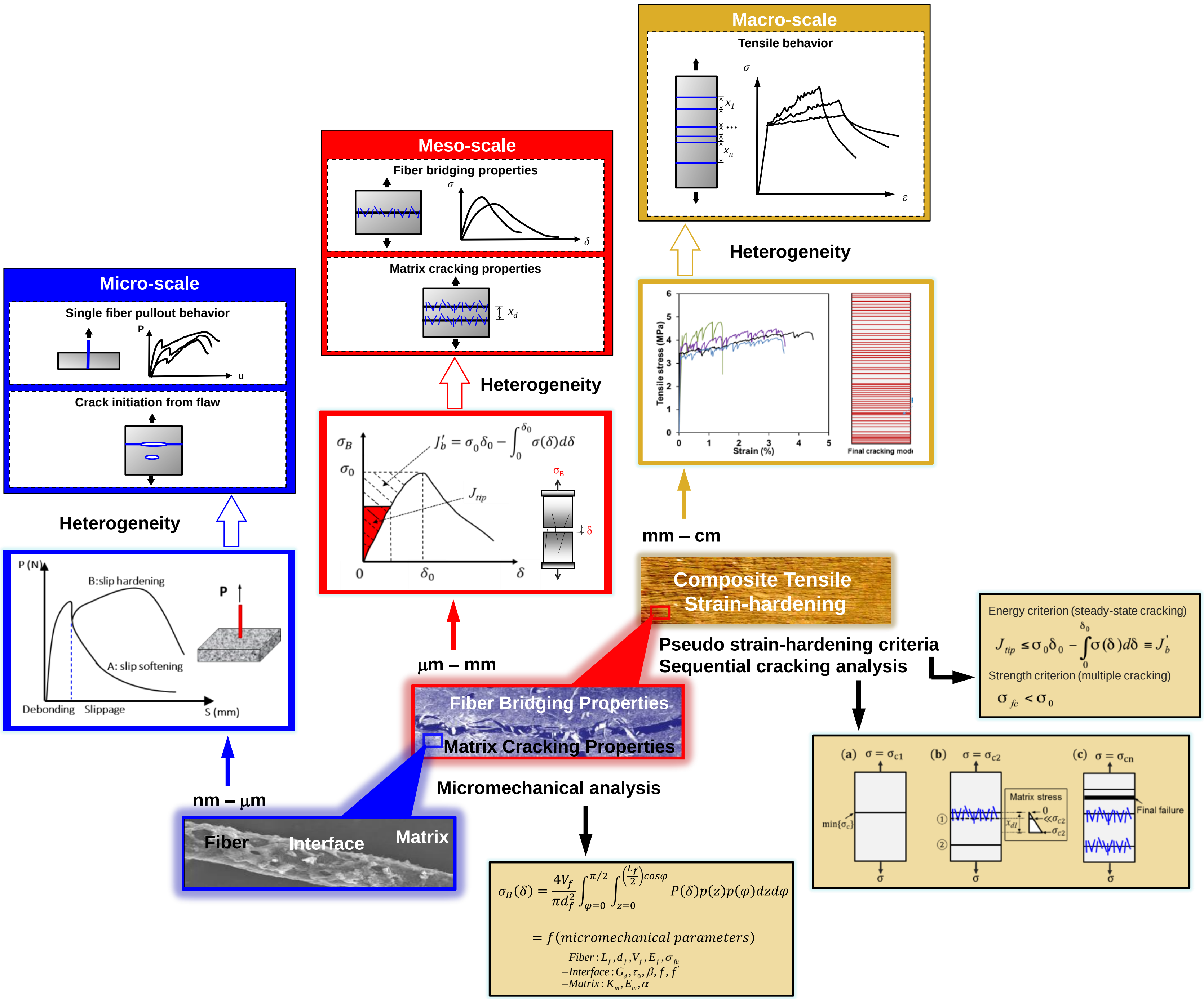
Graphical Abstract



Li: Methodology, Investigation, Writing original draft and Data curation

Qiu: Methodology, Writing-Editing and Review

Weng: Methodology, Writing-Editing and Review

Yang: Resources, Methodology, Writing-Editing and Review, Supervision and Project administration

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: