Cement and Concrete Research 90 (2016) 117–126

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

A micromechanics-based fatigue dependent fiber-bridging constitutive model

Jishen Qiu, En-Hua Yang *

Civil and Environmental Engineering, Nanyang Technological University, Singapore 639797, Singapore

ARTICLE INFO

Article history:
Received 12 April 2016
2 September 2016
Accepted 21 September 2016
Available online xxxx

Keywords:
Analytical model
Fatigue
FRCC
Micromechanics
PVA fiber
Single-fiber

ABSTRACT

Fiber-reinforced cementitious composites (FRCC) represent a large group of construction and building materials. While numerous experimental studies have been conducted on fatigue of FRCC, predicting FRCC fatigue performance remains difficult. This paper proposes a novel multi-scale analytical model to capture the fatigue dependency of fiber bridging constitutive law in FRCC. On the micro-scale, a new analytical model to predict the post-fatigue single-fiber pullout behavior (*P-u* curve) is established based on the understanding of the fatigue dependency of fiber and fiber-matrix interface. On the macro-scale, the fatigue-induced fiber strength reduction was considered and probabilistics is introduced to describe the randomness of fiber location and orientation so that the fatigue dependent fiber-bridging constitutive law can be predicted. The model proposed in this paper is the first analytical model that is able to capture the effects of fatigue cycle as well as the fatigue loading level on deterioration of fiber bridging in FRCC.

1. Introduction

Fatigue is an important factor for the deterioration of many reinforced concrete infrastructure, such as pavement [1], bridge [2], railway slippers [3], and the supporting structure of offshore windmills [4]. Under repeated loading, the intrinsic flaws and micro cracks in concrete would gradually propagate into macro cracks. This reduces not only the structural capacity and serviceability but also the durability as the aggressive acid rain or sea water would penetrate through the cracks. The coupling effect of load repetition and environmental attack greatly shorten the service life of these infrastructures.

Fibers provide effective means to suppress the brittleness of cement-based materials. Under repeated loading, fiber bridging of fiber-reinforced cementitious composites (FRCC) can effectively relieve the stress concentration at the crack tip, thus decelerating the crack propagation and extending the fatigue life of the structure [5]. The extension of fatigue life with increasing fiber content has been observed in FRCC reinforced by various types of fibers, such as steel fibers [6–8], polymeric fibers [9–11], glass fibers [12], and carbon fibers [13]. The effects of fiber dimension on fatigue life, however, remain controversial. For example, Johnston and Zemp [6], on the basis of fatigue test over 100 specimens, concluded that higher fiber aspect ratio, i.e. length-to-diameter ratio, led to higher flexural fatigue strength and extended fatigue life; while Naaman and Hammound [14] noticed in their tests that fiber aspect ratio of 60 and 100 produced similar flexural fatigue strength and fatigue life. Such disagreement indicates the complicacy involved in predicting the fatigue performance of FRCC.

The key to predict fatigue performance of FRCC lies in robust characterization of fatigue-induced crack propagation, the rate of which is determined by the crack-tip stress intensity factor. The crack-tip stress intensity factor is influenced by the quality of fiber bridging, which deteriorate continuously with fatigue loading [15]. Two models have been proposed to predict the fatigue-induced fiber-bridging deterioration of FRCC. In a force equilibrium-based model, Zhang et al. [16] measured the fiber-bridging law, i.e. the tensile stress vs. crack opening displacement curve, with notched cube specimens under tensile fatigue loading, so the fiber-bridging deterioration can be modelled analytically. The limitation of such method lies that micro-scale factors such as fiber geometry cannot be included and that fatigue tests must be conducted once the mix design is changed. In a fracture mechanics-based model, Li and Matsumoto [17,18] established the fiber-bridging law by summing the pullout behavior of individual fibers after fatigue deterioration. In their model, the frictional bond between fiber and matrix interface was assumed to decrease with fatigue cycles without any experimental justification. In addition, chemical adhesion between fibers and matrix was not considered.

Recently, the fatigue-induced fiber and fiber-matrix interfacial deterioration has been experimentally characterized and new deterioration mechanisms have been discovered in a micro-polyvinyl alcohol (PVA) fiber reinforced cementitious composites by the authors [19,20]. To characterize fiber deterioration under fatigue, single PVA fiber was embedded in cement matrix with large embedment length to prevent full debonding of fiber from the matrix. The embedded fiber with different inclination angle underwent tensile fatigue loading at various loading

* Corresponding author at: N1-01b-56, 50 Nanyang Avenue, 639798, Singapore.
E-mail address: ehyang@ntu.edu.sg (E.-H. Yang).

http://dx.doi.org/10.1016/j.cemconres.2016.09.017
0008-8846/

level until fiber rupture. It was found that the in-situ strength of PVA fiber decreased with increasing load cycles. To investigate deterioration of fiber-matrix interface properties, single PVA fiber was embedded in cement matrix with small embedment length so that fiber underwent debonding and sliding from the surrounding cement matrix when subjected to tensile fatigue loading. It was discovered that fatigue load was able to propagate the tunnel crack along the fiber-matrix interface, which was referred as fatigue-induced fiber debonding, and an empirical relation between debonding rate and fatigue loading level similar to the Paris' law was suggested. It was observed that interface chemical bond Gd was fatigue independent while frictional bond τ0 increased with fatigue cycles N and fatigue loading levels Pmax. Such fatigue-induced interface hardening can occur during fiber debonding stage, which was referred as fatigue debonding hardening, as well as during fiber slippage stage, which was referred as fatigue slippage hardening. These phenomena led to premature fiber rupture and may cause severe fiber-bridging deterioration, which needs to be captured with proper model.

In this paper, a micromechanics-based fatigue dependent fiber-bridging constitutive model was proposed by taking account of fatigue dependency in material microstructure which consists of fiber, matrix, and fiber-matrix interface. Parametric study on the influence of fatigue loading level and fatigue cycle as well as fiber surface treatment on the fiber-bridging σ-δ curves was also reported and discussed.

2. Modeling approach: Scale linking

Scale linking represents the approach behind the development of current model as shown in Fig. 1. As can be seen, fibers bridge across the crack and fiber-bridging spring law governs the bridging behavior in the macro-scale (μm–mm). One scale below is the material microstructure (nm–μm) which consists of fiber, matrix, and fiber-matrix interface. This conceptual illustration suggests that performance of fiber bridging in the macro-scale is governed by the properties of component, i.e. fiber, matrix, and interface, in the micro-scale. Specifically, deterioration of the fiber-bridging constitutive law subject to fatigue is a result of fatigue dependencies in fiber, matrix, and fiber-matrix interface micro-scale.

The fatigue dependent stress-crack opening relationship $\sigma(\delta)$, which can be viewed as the constitutive law of fiber-bridging behavior subject to fatigue, is derived by using analytic tools of fracture mechanics, micromechanics, and probabilistics. In particular, the energetics of tunnel crack propagation along fiber-matrix due to fatigue is used to quantify the fatigue-induced debonding process and fatigue-induced changes on the fiber and the fiber-matrix interfacial properties are captured in the micro-scale. The total stress carried across a crack is a composite action of many fibers bridging across this crack which can be express as a summation of the forces induced by each bridging fiber across the matrix crack per unit area. Probabilistics is introduced to describe the randomness of fiber location and orientation with respect to a crack plane. The random orientation of fiber also necessitates the accounting of the mechanics of interaction between an inclined fiber and the matrix crack. As a result, the $\sigma(\delta)$ curve is expressible as a function of fatigue dependent micromechanical parameters.

3. Micro-scale modeling: Fatigue dependent 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 [21]. As shown in Fig. 2, the event of complete debonding (noticed by the sudden load drop from P_a to P_b) divides the single fiber pullout curve into the preceding fiber debonding stage and the following fiber slippage stage.

Based on fracture mechanics-based approach, Lin et al. [22,23] developed an analytical model for monotonic single fiber pullout force-displacement (P-u) relation, as explicitly expressed in Eqs. 1 to 4. In the fiber debonding stage (Eq. 1), the load P is resisted by the chemical bond G_d at the bonded interface as well as the frictional bond τ_0 at the debonded interface. After full debonding, i.e. in the fiber slippage stage, chemical bond diminishes and only the frictional bond dominates pullout behavior (Eq. 2). In this stage, due to the large relative displacement between soft fiber and hard matrix, the fiber surface is abraded and roughened, resulting in stronger friction. Such slippage-induced friction

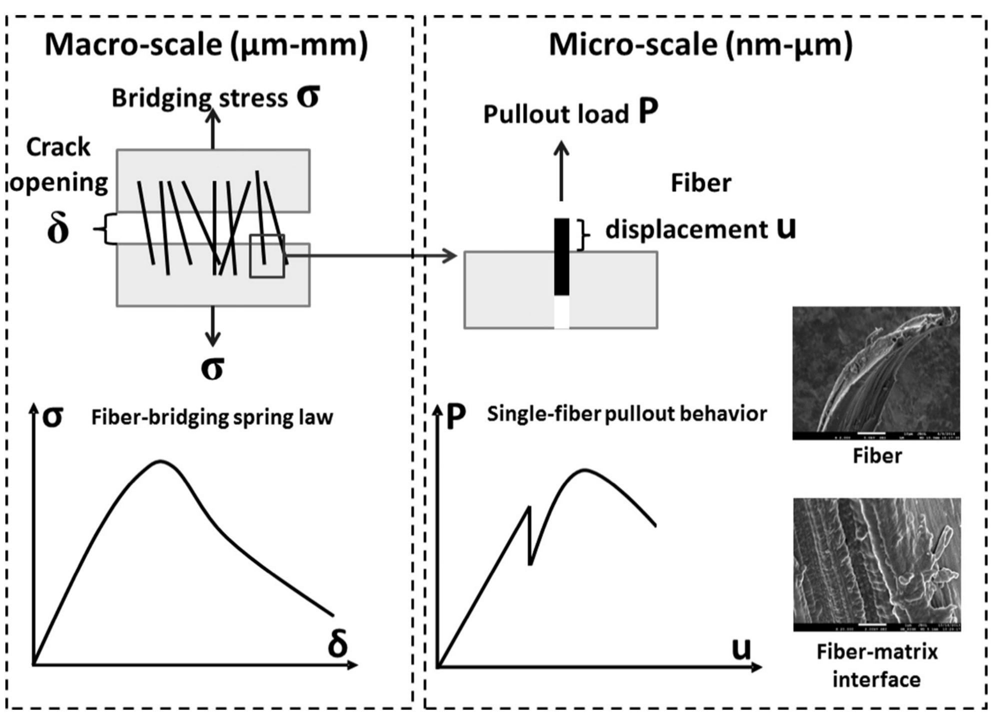

Fig. 1. Illustration of the scale linking in current model.