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Mechanical analyses of hooked fiber pullout performance in ultra-high-performance concrete

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HIGHLIGHTS

- The pullout response of straight and hooked fibers in ultra-high-performance concrete is investigated.
- Spalling due to fracture propagation is proposed which corresponds to the experimental results.
- Friction due to bending, slip-hardening and tunnel damage are explicitly taken into account.
- Pullout behavior in different matrix with variable fibers is properly modeled.

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ABSTRACT

In this study, a practical model to simulate the pullout performance of hooked steel fiber in ultra-high-performance concrete is proposed. Straight and hooked fiber pullout tests were performed to evaluate the pullout mechanism, based on which slip-hardening, matrix spalling and tunnel damage assumptions are made. With energy conservation, static and fracture mechanical analyses, this model investigates the pullout load due to mechanical deformation as well as additional friction caused by bending. Model predictions are compared with the experimental results of hooked fiber pullout data and reasonably good correlation is observed.

1. Introduction

Ultra-high-performance concrete (UHPC) is distinguished for its high compressive strength but it is still weak in resisting tensile stress. Fiber reinforcement makes up for this deficiency [1]. By adding fibers to UHPC, the strain hardening behavior, ductility and energy absorbing capability can be greatly enhanced. When crack occurs, fibers bridging the potential cracks are activated to provide resistance to crack propagation. The fiber bridging force comes from the transfer stress at the fiber–matrix interface, which is achieved by the bond defined as the shear stress acting on the interface. The bridging action provided by the fibers strongly depends on the pullout mechanism [2]. Accordingly, it is necessary to study the bond properties between matrix and fiber. As a part of the research to characterize the tensile property of fiber reinforced ultra-high performance concrete, fiber–matrix bond behavior is assessed through single fiber pullout experimental investigations and mechanical analyses.

In the past few decades, extensive experimental programs have been conducted to investigate the steel fiber pullout behavior, which dealt with the physical parameters such as fiber geometry, orientation, tensile strength, embedded length and mortar strength [3–7]. Based on straight fiber pullout tests in different grouts, Naaman et al. [3] indicated that the fiber geometry (smooth and hooked) as well as mortar matrix strength can significantly change the pullout response. With respect to ultra-high performance concrete, Shannag et al. [8,9] studied the effect of fiber length as well as matrix strength on the interfacial bond-slip property, while Orange [10] investigated the influence of surface treatment of the fiber. More recently, Wille and Naaman [4] performed a comprehensive fiber pullout tests in UHPC, which showed that hooked-end fiber with a smaller diameter and smaller angle of the end hook could gain more pullout resistance.

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Mechanical analyses were also adopted to investigate the pullout behavior and in turn gave instructions about fiber reinforced concrete casting. Lin et al. [11] and Naaman et al. [1] separately developed bond-slip analytical models to describe the straight fiber pullout performance and both achieved great success. Shrink fit coupled with decay of misfit were proposed by Naaman et al. [1] to explain the bond deterioration during sliding phase for normal concrete while Bao and Song [12] assumed that the abrasion and jamming effect could result in slip-hardening which accounted for some experimental curves observed [13,14].

Models for hooked fiber pullout response are mainly built with energy conservation, fracture mechanics and empirical analyses [2,15–19]. Based on the principle of energy conservations, Chanvillard [15] addressed the mechanical component of bond of crimped fibers in his fiber pullout model which accounted for plastic deformation and residual friction at the points of inflection of the hook. Alwan et al. [17] used a frictional pulley along with two plastic hinges to simulate the hook action, and proposed a fictional pulley model to predict the pullout behavior of hooked steel fibers. Empirical models based on principles of inverse analysis procedure were also applied to analyze the pullout behavior. Based on exclusive experimental data, Laranjeira et al. [18] took the contribution of the hook into account through key points to describe the pullout response of aligned fibers. Subsequently, an analytical model [19] was proposed to predict the inclined hooked fiber pullout behavior by subtracting the pullout load of aligned straight fiber from the pullout load of aligned hooked fiber.

Although fiber pullout behavior has been largely investigated, the existing fiber pullout models are not sufficient for the pullout model in UHPC. Consequently, mechanism of fiber pullout in UHPC needs to be better characterized. Focusing on a single fiber pullout in UHPC, this paper builds a mechanical model for hooked fiber pullout in UHPC by combining energy method and empirical estimation to form a new practical model. Experimental tests with different fiber geometry and embedment length are conducted to feature the bond shear stress and the geometry influence.

2. Experimental investigation

2.1. Materials and specimen

Both straight and hooked steel fibers were used in the tests to analyze pullout response. Young's Modulus and tensile strength of the steel fibers are reported by the manufacture to be 210 GPa and 1.345 GPa, respectively. The hooked fiber measured geometry is illustrated in Fig. 1 and Table 1 where footnote "a" clarifies the specimen embedment length.

The water/cement ratio of 0.208 was employed to cast the pullout specimen. Aggregate size ranged from 0.3 mm to 0.6 mm. The detailed mixture is listed in Table 2. After casting and adequately vibrating, the specimens underwent a curing regimen. At first, specimens were placed in an environmentally controlled room at 22 °C and 100% humidity, and then they were demolded 24 h later. After 7 days curing, these specimens were submerged in a water bath maintaining 90 °C for 4 days. Finally, they were dried in an oven at 90 °C for an additional 2 days. The compressive strength of UHPC was achieved by uniaxial compression tests with 75 mm diameter by 150 mm high specimen. At the age of 14 days, the average compressive strength f'_c was 230 MPa, and Young's modulus E_m 55 GPa.

Before hooked steel fiber pullout analyses, straight fibers pullout experiments were tested to evaluate the bond and friction of the fiber/matrix interface. Straight fibers were obtained by chopping the hooked-ends of the hooked fibers. Specimens were prepared with fiber embedment length 12.7 mm (0.5 inch) for straight fiber

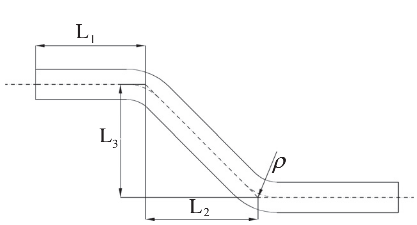

Fig. 1. Fiber geometry.

Table 1
Geometric properties of the hooked-end.

Specimen no.	ρ (mm)	L_1 (mm)	L_2 (mm)	L_3 (mm)
5 #	0.8	2.26	1.08	2.01
6 #	1.02	2.2	1.3	1.64
7 #	0.98	2.13	1.27	1.69
8 #	0.93	1.95	1.12	1.88
9 #	0.81	1.99	1.29	1.86
10 #	0.92	2.14	1.21	1.63
11 #	1.03	2.12	1.3	1.75
12 #	0.87	1.98	1.17	1.88
Mean	0.92	2.11	1.22	1.79

[a] 5–8# are used for 6.35 mm embedment length tests, 9–12# are used for 12.7 mm embedment length tests.

Table 2
UHPC mixture composition.

Material	Cement	Sand	Silica flour	Silica fume	Super plasticizer	Water
Proportion by weight	1	0.967	0.277	0.389	0.0171	0.208

pullout tests. While the hooked fiber pullout tests were conducted with 12.7 mm (0.5 inch) and 6.35 mm (0.25 inch) length embedded, as shown in Fig. 2. Fibers were pulled out under displacement control with a loading rate of 0.5 mm/min. Each set of experiment was conducted with 4 specimens to get a practical scatter. Straight fiber pullout tests used specimens were noted 1–4. While specimens numbered 5–8 and 9–12 were prepared for hooked fiber pullout tests with 6.35 mm and 12.7 mm embedded length, respectively.

2.2. Results of pullout testing

Experimental results of pullout curves of straight fibers are plotted in Fig. 3 where the darkened curve is the mean value of the experimental data. After the peak load is reached, a rapid and slight decrease of the pullout load is observed in Fig. 3(a). Afterwards the pullout load shows a stable slight increase followed by a gradual decrease to zero during purely sliding. By dividing the pullout load by the current nominal embedded fiber cylindrical surface, the pullout load versus slip relationship can be transformed into the shear stress versus slip relationship in Fig. 3(b). Comparing with the previous research [16], a significant difference is observed in Fig. 3 that the nominal average shear force exhibits a continuous increase after the peak, thus achieving a bond-stress versus slip hardening behavior.

Pullout response of hooked steel fiber shown in Fig. 4 exhibits a different mechanism of pullout behavior due to the geometry effect. For 6.35 mm embedment length fiber pullout test, the pullout load experiences a hardening due to hooked end mechanical deformation. Since the embedment hook is near the matrix free surface, it tends to show a weaker bond with contrast to Soetens's work [5]. While the 12.7 mm embedded fiber undergoes a more complicated pullout process in terms of pullout load–slip relationship. The pullout load drops rapidly after peak because of debonding and tunnel damage and then it increases slightly due to the bending of the first hook toward the opposite direction. After the embedded tip exits the curved tunnel, the straightened fiber slides along the straight matrix tunnel which coincides with the pullout response of straight fiber pullout response shown in Fig. 5.

3. Analytical pullout model for straight fiber

The straight fiber pullout process consists of bonded, debonding and sliding phases. When pullout load is not sufficient to separate fiber and surrounding matrix, the fiber–matrix interface keep bonded. With the increase of the slippage, debonding occurs, namely part of the fiber begins to slide along the matrix channel while the other part still remains bonded. After debonding phase, sliding prevails which is considered as the result of shrink-fit theory [3,16]. As the fiber pullout continues, the fiber–matrix may deteriorate due to abrasion and compaction of sand and cement particles or harden due to jamming effect [13].

3.1. Debonding and frictional slip

The mathematical derivation of straight fiber pullout has been extensively formulated by Naaman et al. [1].