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High loading-rate pullout behavior of inclined deformed steel fibers embedded in ultra-high performance concrete

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HIGHLIGHTS

- The pullout behavior of inclined high strength steel fibers embedded in UHPC is investigated.
- The influence of fiber geometry, embedment inclination, and pull out rates are studied.
- Pullout resistance increases with inclination angle and loading rate up to point, beyond which matrix spalling at the fiber's exit point dominates behavior and adversely affects pullout resistance.
- Pullout energy dissipation is sensitive to the loading rate and inclination angle in a manner that parallels pullout resistance.

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ABSTRACT

Single fiber pullout tests enable a deeper understanding of the behavior of fiber reinforced cementitious materials. The vast majority of fiber pullout tests in the literature are quasi-static and conducted with fibers aligned in the loading direction. Studies that focus on dynamic or inclined pull out behavior are not common and those that combine both effects are rare. In this paper, the experimental study investigates the effects of embedment inclination and pullout rate on the behavior of high strength steel fibers embedded in an ultra-high performance concrete (UHPC) matrix. The experimental variables are fiber type (straight smooth, hooked and twisted), embedment inclination, which varies from zero (aligned with load) to 45°, and loading rate, which ranges from 0.018 mm/s (representing quasi-static loading) to 1800 mm/s (representing impact loading). Test results show that the load and energy dissipation capacities for straight smooth fibers generally increase with loading rate and inclination angle up to 45°. The hooked and twisted fibers exhibit less consistent trends and their peak load and energy dissipation capacities occur at inclination angles that range from 0° (aligned with load) to 30°. The straight smooth fibers exhibit the most sensitive response to loading rate and achieve a load capacity dynamic increase factor (DIF) as high as 2.32. The DIFs are generally less for hooked fibers and drop below 1.00 for twisted fibers, especially at higher inclination angles.

1. Introduction

Ultra-high performance concrete (UHPC) exhibits outstanding mechanical characteristics with a compressive strength in excess of 150 MPa. The extraordinary strength stems from optimizing the gradation of its granular constituents to achieve a high particle packing density of the matrix [1–3]. UHPC also exhibits exceptional long term properties as result of the matrix's discontinuous pore structure [4,5].

When properly reinforced with steel fibers, UHPC displays strain hardening behavior and excellent post-cracking behavior. As a fiber reinforced cementitious composite, UHPC resists tensile forces through composite action between the matrix and fibers. Once a crack occurs, fibers bridge the crack, resisting further crack growth and propagation. This type of behavior promotes multiple cracking prior to crack localization, leads to strain hardening response and is directly responsible for the material's high energy absorption capacity. The behavior of UHPC in tension, particularly its post-cracking response, is directly dependent on the fiber-matrix interaction that occurs during fiber pullout [6–9,3].

Wille et al. [7,8] recently investigated the optimization of strength and ductility of UHPC under direct tensile loading. UHPC

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with a compressive strength between 150 and 200 MPa and high-strength steel fibers was considered. The results showed that the UHPC exhibited strain hardening behavior, high tensile strength (up to 15 MPa) and 0.6% strain capacity at a relatively low fiber volume fraction (about 2%). Wille et al. [9] and Pyo et al. [3] investigated the uniaxial tensile behavior of UHPC under different strain rates ranging from quasi-static (0.0001 1/s) to seismic (0.1 1/s). Different high strength steel fiber types (straight, hooked, twisted) with volume fractions of 1.5%, 2%, 2.5%, and 3% were used in this study. It was shown that post-cracking strength, softening strain capacity, and energy absorption capacity were all substantially influenced by the strain-rate.

Single-fiber pullout tests, where fiber slip is evaluated as a function of the applied load on the fiber, are useful for assessing the bridging effectiveness of fibers. The data obtained from such tests can provide useful insight into how to enhance the mechanical properties of steel fiber reinforced cementitious composites. There is consensus that fiber-matrix debonding and frictional sliding are the two most important resistance mechanisms governing the pullout behavior of straight fibers [10–12]. In addition to these two mechanisms, deformed fibers also mobilize mechanical anchorage during pullout. For example, hooked and twisted fibers tend to straighten or untwist, respectively, when pulled out. The mechanical anchorage part of the response complicates pullout behavior and has been the subject of numerous studies in the past [6,13–20].

Alwan et al. [10] used a frictional pulley with two plastic hinges to simulate the hook's behavior and proposed a model to predict the pullout behavior of hooked steel fibers. Sujivorakul et al. [14] extended the straight fiber pullout model by adding a nonlinear spring at the end of the fiber to model the effect of mechanical anchorage. Robins et al. [15] reported that the pullout behavior of hooked fibers is predominantly influenced by matrix strength, fiber embedment length, and orientation of the fiber. Laranjeira et al. [16] developed a model to predict the pullout behavior of hooked-end steel fibers. The effect of the hooked-end was experimentally evaluated by subtracting the pullout curve of a straight fiber from the pullout curve of a corresponding hooked fiber.

Twisted fibers display behavior that is different from that of either straight or hooked fibers. Twisted fibers provide mechanical bond that is uniformly distributed along its length. To explain the reinforcing effect, Naaman et al. [17–19] identified a set of factors that influence the bond characteristics of twisted fibers, including cross-sectional shape, twist pitch, mechanical properties of the matrix and fiber, and embedment length. Based on Naaman's studies, Sujivorakul [20], developed an analytical model to predict the pullout behavior of a twisted fiber. Kim et al. [21] explored the flexural response of beams loaded in four point bending and made with a variety of fibers, including twisted fibers. They concluded that the specimens reinforced with twisted fibers showed the best performance in almost all aspects of behavior including load carrying capacity, energy absorption capacity, and multiple cracking behaviors.

Most single fiber pullout investigations have been quasi-static. However, a few studies under dynamic pullout loading have been carried out. Gokoz et al. [22] carried out fiber pullout tests under various loading velocities for a variety of fiber types, including smooth steel fibers. Abu-Lebdeh et al. [23] investigated the influence of loading rates on pullout behavior from very high strength concrete. Banthia et al. [24,25], Kim et al. [26] and Xu et. al. [27] evaluated the effect of loading rate on the pullout behavior of several types of deformed steel fibers. Another notable study that addressed fiber pullout at different rates of loading can be found in [28]. The general findings from these studies indicate that increases in loading rate lead to increased bond strength and energy dissipation capacity, although conflicting trends have been reported, e.g. in Ref. [24].

The vast majority of studies on fiber pullout behavior have been conducted with fibers aligned in the loading direction because such tests are easier to conduct than inclined fiber tests. The few studies that have addressed inclined fibers noted that fiber inclination has a strong influence on pullout load and energy dissipation under quasi-static loading [13,16,29–34]. Naaman et al. [29] suggested that the pullout energy required to pull out an inclined fiber completely was higher than that for a corresponding aligned fiber. Several studies reported similar findings [13,30,31,33] and concluded that pullout resistance and energy absorption capacity are maximum at inclination angles between 30° and 60°. Li et al. [30] indicated that the pullout load for inclined nylon and polypropylene fibers is a function of the inclination angle and suggested that pullout of a flexible fiber from the matrix is analogous to a friction pulley, termed the snubbing effect. The snubbing mechanism does not occur in steel fibers as clearly as it does in polymeric fibers because the high elastic stiffness and strength of steel fibers promote premature matrix spalling. To address this issue, Lee et al. [31] considered the effects of both snubbing and matrix spalling when modeling the bond behavior of inclined fibers embedded in an ultra-high strength matrix.

As noted in the previous paragraphs, just a few studies have investigated the effects of inclination angle or loading rate on fiber pullout behavior. Studies that have studied the combined effects of fiber inclination angle and loading rate are extremely rare. To the knowledge of the authors, there are no studies that have addressed both issues together when the matrix is UHPC, hence the research reported herein. As such, the objective of this work is to evaluate the effect of inclination angle and loading rate on the pullout behavior of various types of steel fibers embedded in UHPC. The primary experimental variables are fiber type (straight smooth, hooked, and twisted), inclination angle of the fiber, and loading rate.

2. Pullout behavior of aligned and inclined fibers

Fig. 1a shows the typical pullout behavior from an ultra-high strength cementitious matrix for aligned straight smooth, hooked and twisted fibers, hereafter referred to as S-, H- and T-fibers, respectively. As an aligned S-fiber is loaded, the pullout force increases until its debonding capacity is exceeded and the fiber slips. The peak pullout resistance is controlled by the physico-chemical bond properties between the matrix and the fiber. After slippage initiates, the S-fiber suffers a rapid drop in load that levels off as the slip level increases. Tai et al. [28] noted that the UHPC matrix can scratch and gouge the fiber surface as it is pulled out, contributing to post-peak energy dissipation capacity.

The pullout behavior of aligned H-fibers (Fig. 1a) is characterized by an initial steep increase in load. The bending resistance of the fiber at the hooked end induces pressure on the cementitious matrix, which increases the frictional force and causes corresponding increases in the pullout strength. The post peak response of H-fibers has a distinctive two-drop shape, where each drop corresponds to the formation of a plastic hinge at the hooked end as the fiber straightens and gradually pulls out. Since the straightening is not complete, the 'wavy' end portion of the fiber causes increased friction in the pullout tunnel, contributing to post peak pullout resistance. Under dynamic pullout, the high forces in the fiber can lead to localized micro splitting cracks at the bend points of the end-hook due to high mechanical anchorage. The localized matrix damage contributes to the rate effects associated with H-fibers during pullout as theorized in [27].